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Optical Problems Facing the Navy*

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OPTICAL instruments find many uses in our Navy, so many that I shall not attempt to enumerate them. The greatest optical problem facing the Navy today is procurement. We need more rangefinders, telescopes, and gun sights than can be produced even by this country's greatly expanded optical industry. The Navy appreciates the efforts in the national defense being made by our leading optical companies, and it is encouraging these companies and others to continue to expand existing facilities. The bottleneck is not so much in raw materials as it is in machinery and men for producing the finished products. Machine tools are needed in the optical industry as they are in other industries, and skilled hands are necessary also. But in order to carry out the two-ocean Navy program we must find production short-cuts and improved mass-production methods. We must search for acceptable simplifications of design and for substitutes that involve different procurement problems. For this reason we are interested in the advent of plastics as a supplement for glass in the optical field, particularly when the processes of grinding and polishing can be partially or totally dispensed with. Again, the production of solid glass color filters is lagging somewhat, so we are encouraging the production of ray filters of the laminated type. These should excel in reproducibility, but the problem of their ultimate stability is not yet entirely solved.

But I should like to turn from the production problem, which is already well understood by those concerned, to a general discussion of the two major uses of optical gear in the Navy. These are: first, navigation, and, second, fire control.

Navigation is a very old science, and it employs what is perhaps the simplest optical instrument of them all, the sextant. This instrument, in combination with the chronometer and the compass, makes possible ordinary navigation. Of course, we have some modern inventions which have come to play an important part in navigation, and the problems of aerial navigation are more complicated than those faced by the navigating officer aboard ship. But it is doubtful whether the day will ever come when the navigator does not shoot the sun and the stars, using an instrument so simple in principle that it could be sketched by any sophomore physics student. Speaking of modern inventions, I should not fail to mention the submarine periscope. This instrument in its modern form is a truly remarkable assemblage of optical parts. It performs searching, navigational, and fire control functions, acts as a telescope and makes possible estimates of

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the range, relative speed and bearing of the target, which estimates must be made in the course of a few seconds, and while the submarine skipper is located in the conning tower, perhaps forty feet below the surface of the ocean. Periscopes must be sturdy enough to stand the strain of being pulled through the water at a speed of ten knots or more, must be watertight against a pressure of a hundred pounds per square inch, and must be shaped so as to leave no telltale wake that will reveal to scouting planes the presence of the submarine.

THE FIRE CONTROL PROBLEM

The primary purpose of a present-day shooting Navy is to be able at a moment's notice to hurl defiance at the enemy; defiance that takes the form of shells, torpedoes, bombs, or depth charges. The fundamental problem involved in this hurling operation is that of *fire control*, and fire control is without doubt the most technical problem facing the modern navy. By fire control is meant the process by which shells, bombs, or whatnot, are correctly fired or released so as to reach the desired destination, which is usually an enemy ship or plane. We are all familiar with the elementary concept of pointing the gun at the object you want to hit, with the superelevation necessary because of the parabolic trajectory of the bullet, and with the necessity of taking into account the time of flight of the bullet, in the case of a moving target, by aiming somewhat in front of the target. But the fire control problem aboard ship is much more complicated than this; there is always the pitch and roll of the ship to consider, for example.

The most advantageous position for viewing enemy craft is not, of course, by the main battery guns, but is up in the fire control tower. In present-day battleships, the firing is indeed controlled from this position, which may be many yards away from the guns themselves. This necessitates a complicated and yet accurate system of control which in the most modern ships is refined to the stage where the gunnery officer, from his point of vantage, can direct the fire of any, or all, guns, both main and secondary battery, either simultaneously or individually, and at either a single target or at several targets.

The new, *big* thing that the present war has brought is the anti-aircraft defense problem, which during World War I was relatively insignificant. But such are the military characteristics of the present-day bomber and torpedo plane that methods of defensive armament have of necessity been profoundly changed. An aircraft target is much faster moving and more highly maneuverable than a surface target. This means greater relative velocities and hence much greater lead angles necessary in firing. It also means that there is much less time available to man, train, and fire the guns, particularly in the case of surprise attacks. In addition, anti-aircraft fire other than that of the machine gun type employs shells that burst at a predetermined range. This adds another variable to the fire control problem, namely, that of fuze setting. The fuze on each projectile must be properly set and the time for handling the shell between fuze setting and firing must be held as constant as is humanly possible.

These remarks have dealt chiefly with the fire control problem as applied to guns. There are also problems concerning torpedo and bomb control, but I shall not discuss these for several reasons, one of which is the lack of time! Suffice it to say that much research is being done along these lines; new bombsights and new processes in bomb control are constantly being considered and developed.

The first step in fire control is to locate the enemy, and to this general problem the term *searching* is applied. We are all familiar with the picture of the lookout in the crow's nest constantly scanning the horizon, and now also the skies, for possible approaching enemies. His is an optical problem. Unfortunately, ordinary binoculars, or ordinary human eyes, are not too successful here. A little haze or smoke will obscure approaching ships most successfully. Glare on the water can be reduced by polarizing goggles, a modern development. But it has been general experience that surprise airplane attacks can come so rapidly that the guns cannot be manned or trained before the torpedoes or bombs are released and the invading planes have escaped. Evidently some more efficient searching method is needed, and, as you know from reading the newspapers, such methods are rapidly being

developed. Suffice it to say that our Army and Navy are letting no grass grow under their feet in this matter.

RANGEFINDERS

Having located an enemy craft, it is necessary to make certain observations and computations before firing the guns. The primary observational instrument is the *rangefinder*. By this instrument, plus its auxiliary telescopes, it is possible to obtain three coordinates, azimuth, elevation angle, and slant range, which serve to locate exactly his position with reference to yours. Then computations must be made which will serve to locate the target at a later time, determined by the time of flight of the projectile. Prediction methods have been worked out satisfactorily by the Coast Artillery, and among other factors must allow for the parallax caused by the distance apart (in some cases, several hundred yards) of rangefinder and gun battery. As mentioned before, the problem is further complicated for both ships of the sea and ships of the air by the necessity of allowing for their pitching and rolling motions. Needless to say, it is here that the gyroscope plays an all-important role.

Rangefinders are of two general types: coincidence and stereoscopic. The modern coincidence rangefinder was developed by Barr and Stroud of England in 1888 and has always been the favorite of the English Navy. It utilizes monocular vision, splits the target image (preferably a mast or smoke stack) into two parts, and indicates correct range when the two parts are brought into coincidence. The coincidence rangefinder is easy to use and is successful in ranging on surface craft where appropriate target images are usually available. It is used in over half of our main-battery turrets. The stereoscopic rangefinder received its chief development at the firm of Zeiss and has always been the German favorite, having been in common use on German ships during the last war. The fact that the Germans used stereoscopic rangefinders while the English used coincidence rangefinders has resulted in a further examination of the results of the Battle of Jutland, the only large encounter between two modern naval forces. However, the results of this famous battle are not clearly enough defined so that they can form the basis for a choice between the two types of rangefinders.

The stereoscopic rangefinder is a binocular instrument in which accuracy of setting depends greatly upon the training of carefully selected observers. It is believed to be the superior instrument for use in ranging on small or indistinct targets. My personal feeling in the matter is as follows: When there are available satisfactory targets, that is, targets with vertical straight lines upon which coincidence settings can be made, the coincidence instrument is faster to set and gives a feeling of confidence—you feel that you simply *cannot* have anything but the right range. On the other hand, it is difficult if not impossible to make a satisfactory coincidence setting on a small, irregular image such as that of a distant airplane. True, an astigmatizer lens may be cut in to elongate the point source into a line, but this can be used to advantage only with bright, contrasting sources such as the masthead lights of a ship, at night. Therefore, in anti-aircraft observation the preference in most countries is toward the use of stereoscopic rangefinders. The surprising thing to one new in this field is that such an apparently difficult judgment as that involved in setting a stereoscopic instrument can be made with the high accuracy and reproducibility that is attained by experienced observers.

Present-day rangefinders vary in length from 12-inch hand-held instruments to the large battleship turret rangefinders that are over forty feet long. The smallest rangefinders in current naval use are the one-meter navigational instruments used for such purposes as maintaining a ship's proper position in formation. The standard formula for rangefinder errors has the base length in the denominator, which means that the greater the length the greater is the accuracy attained. Attention must be given, however, to practical considerations of size and weight. The difficulty of mounting the instruments, and the torque necessary to train them on the target, must be considered. In fact, in deciding on the size to build a new rangefinder, a compromise must be made between instrumental accuracy desired and the space available in that particular position on board ship.

Problems involved in rangefinder operation are caused by the haze encountered at sea, by the necessity, at times, of looking directly into the sun, and by the vibration of the instrument, caused by the ship's operation and by the firing of the guns. Imagine an optical instrument fifteen feet long and measuring angles to *less than one-half second*, all this mounted on a superstructure fifty feet above a rolling and pitching deck, subjected to extreme acceleration when guns are fired and to severe blast pressures. This is the situation faced by the present-day battleship anti-aircraft rangefinder. Imagine the acceleration experienced by the main battery rangefinders that are mounted as integral parts of 16-inch triple turrets, when all three guns fire simultaneously!

The above remarks give some idea as to the problems faced by the manufacturers of these instruments. I have not discussed the more obvious non-laboratory conditions that must be considered, such as rapid changes of temperature and exposure to salt spray and rain.

But particularly in the case of stereoscopic rangefinders, one is dealing not simply with an optical instrument, but with an instrument-operator combination. Thus the physio-psychological response of the operator merits, and is now receiving, grave consideration. The first problem here is the selection, from the thousands of available candidates, of the proper persons for training as rangefinder operators. These men, in a sense, are the prima donnas of the ship (and incidentally, on German ships they enjoy the privileges of prima donnas) for on their rangefinder performance may depend the life of the ship and all its crew. This is particularly true regarding the first few salvos fired, for after that the gunnery officer may introduce arbitrary corrections to account for what appear to be systematic errors in range, elevation, or bearing in the fire. This process is called "spotting" and is carried out, in the case of main battery firing, with the aid of observation airplanes. However, in anti-aircraft fire against dive bombers it may "all be over" before any spotting corrections can be introduced, so the accuracy of the original ranges is all the more important.

But to come back to the personnel problem—having selected operators, the Navy trains them in special rangefinder schools. They must come up to high standards of precision and reliability before they are qualified for rangefinder operation aboard ship. With our present rapidly expanding Navy this problem of training rangefinder personnel has attained added importance. We are attempting to develop better selection methods and better training methods so that our new ships may be manned by the best possible operators.

Another personnel problem, and an all-important one, has to do with the fatiguing of rangefinder operators. How long, under battle conditions, can a man continue to make accurate stereoscopic judgments? What will be the effect on his precision of performance of his emotional response to the battle—apprehension, startle, perhaps fear and terror? These subjects are receiving careful consideration.

OTHER OPTICAL INSTRUMENTS

The rangefinder is doubtless our most valuable anti-aircraft fire control optical instrument. Another important type of instrument is the gun sight. The simplest gun sight is the so-called open sight similar to the one that we used on 22-caliber rifles, as boys. These are somewhat modified on machine guns to what is known as ring sights; the rear sight consists of several concentric rings which aid the gunner in allowing for the relative velocity of the target. Then the hunting rifle has its telescopic sights, and these find their analogues on naval guns. Somewhat more complicated are the collimating "illuminated" sights in which an auxiliary optical system projects the point of aim to infinity. Gun sights for turret guns are really periscopes, since the line of sight must be carried from inside the turret up through its roof, and then projected parallel to the bore of the gun. There are many other types of sights necessary, particularly for aircraft use, and developments in this field are being given high priority and are proceeding with especial rapidity.

Among other optical instruments in fire control, I will mention two, the gun camera and the machine gun training device. Gun cameras are mounted in place of the actual gun and take pictures of what the gunner hits, or rather what he *would have* hit, had there been a gun actually

firing. These are particularly useful in training aircraft gunners; they save ammunition and allow him to fire at accompanying friendly aircraft with impunity. The machine gun training devices, on the other hand, show by projecting stereoscopic tracer bullet images or simulated shell bursts how the gunner fared in firing against moving-picture-reproduced targets. These devices incorporate mock guns with the same "feel" as the genuine article. They make possible the large-scale training of gunners, both aircraft and anti-aircraft, against realistic target scenes, but without the expenditure of a large amount of target-practice ammunition. The Navy has already under procurement three different types of machine-gun training devices and is interested in several others.

RESEARCH

Persons outside the service, especially scientists, often ask us whether the Navy is doing research along lines to improve its armament efficiency, or whether it is just standing pat on current practices until the war is over. Naturally, detailed information along this line is closely guarded at the present time. But I can assure you that research activity is greater now than it has ever been before in the history of the Navy. I wish I could tell you, as an example, about the research work that is being done on rangefinders. It involves the full-time or part-time services of more than a score of the country's leading scientists, who have been loaned for government work by their respective educational, scientific, or commercial employers. The governmental agency that is administering most of the new defense research work is the National Defense Research Committee, or more properly the Office of Scientific Research and Development, of the Executive Office of the President. The rangefinder work is a small, though important, fraction of the total N.D.R.C. program.

Optical research continues to be carried on directly by the Navy, both in the Optical Section of the U. S. Naval Gun Factory in Washington, and at the Naval Research Laboratory at Anacostia, D. C. In the Navy Department itself there are many officers whose sole duty is to keep abreast of scientific developments. In these days of emergency, production and procurement follow very closely on the heels of research and development. Whereas in pre-war days it was possible to test pilot models in a leisurely fashion before proceeding to large-scale procurement, it is now necessary, in the interests of national defense, to take a new device from the "breadboard model" almost directly to the production line. This means that development details must continually be inserted into the production processes. This is admittedly not the most desirable procedure, but it is the only possible method in a country which, in times of peace, does not fully prepare for possible times of war.

In the Navy Department every effort is made to expedite the development of new and worthwhile ideas. The machinery by which this is carried out in the Bureau of Ordnance is as follows: There is a separate division of Research and Development, which has grown from four officers in March, 1941, to over forty in October —a tenfold gain! Each of the officers of this division must keep in touch with the commercial, industrial, service, and N.D.R.C. developments assigned to his cognizance. This involves the establishing of personal contacts, and the making of frequent trips to research and industrial institutions. New ideas and instruments are evaluated by the Research Division, and, if endorsed, are recommended to the Production Division. The Production Division handles the actual procurement details. The third division of this functionally organized Bureau is the Division of Fleet Maintenance. It is the duty of this group to attend to maintenance, repair, and replacement details on all naval ordnance equipment. Each of the three functional divisions is divided into materiel sections such as ammunition, guns and mounts, torpedoes, and fire control.

It should be mentioned that the drawing up of specifications for the manufacture of fire control equipment is by no means an arbitrary matter. There are only a limited number of manufacturers who have the facilities to produce these highly technical instruments. Therefore, it would be silly to lay down specifications which would be practically impossible to meet. Bureau representatives must consult with the manufacturers in this matter, in an effort to get the best possible instruments in the shortest possible

time. In some cases only *performance* specifications are made; the details of arriving at a device which will meet these specifications are left almost entirely up to the manufacturer. All this simply illustrates the cooperation necessary between the armed services and the civilian suppliers of equipment. Naval Inspectors of Ordnance and Inspectors of Naval Material are assigned to many of the larger manufacturing plants. These gentlemen have their offices within the doors of the plant and work in close cooperation with the executives of the company. Their purpose is in no sense to "spy" on the company, but to assist it in meeting its contracts, and in supplying the Navy with necessary materials and equipment with dispatch.

CONCLUSION

I have sketched the general fire control problem, and have spoken particularly about optical matters, as is appropriate on this occasion. I have stated that research and development are proceeding at a greatly accelerated rate. I have indicated that it is the purpose of the Research and Development Division of the Bureau of Ordnance to keep in touch with the newest ideas and the latest inventions. Now I should like to mention a few subjects that will be familiar to you all, to indicate that the Navy is following closely the developments in these fields:

The possible use of plastic materials for lenses and prisms was mentioned above.

Non-reflecting films on optical surfaces have been the subject of much discussion in the scientific literature. We have experimented with the application of these films to the surfaces of binocular lenses as well as in other instruments, and expect shortly to reduce this to a routine production matter.

The infra-red is a region of the spectrum whose potentialities in military matters have been the subject of much discussion, not only in the Sunday supplements, but also in reputable scientific journals. We are following closely the infra-red subject, and have under consideration at the present time several methods for its utilization.

Variable density neutral filters for telescopes and rangefinders are now supplied in the form of Polaroid disks that can be crossed and uncrossed by the observer, to regulate field brightness to the desired amount.

The use of scotopic vision is receiving serious consideration, and will doubtless find wide applicability in searching and fire control problems at night time.

These are but a few of the modern developments in optics that are receiving attention. There are many others, but time and the considerations of security do not permit their discussion today.

Lenses for Aerial Photography*

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THE earliest photographs[1] from the air were made in France, where aeronautics has always exerted a fascination for the man of ingenuity and enterprise. As far back as 1856, M. Nadar took photographs over Paris from a captive balloon, using (presumably) wet collodion plates. Later, in 1885, Tissandier and Ducom used dry plates from a free balloon. Other pictures, somewhat unsuccessfully, were made with cameras supported by a kite. Our earliest record of the use of aerial photography in military work was the photography of enemy fortifications in China from a balloon by Colonel Renard, in 1900. Apparently, the first photographs to be made from an airplane were taken by Wilbur Wright in April, 1909.[2]

PHOTOGRAPHY IN THE WORLD WAR, 1914-18

Just prior to the commencement of the war of 1914–18, one or two workers in the French army, notably a Captain Saconney, were attempting photography from airplanes, but very little official interest was shown in the matter. However, after a Zeppelin captured on August 22, 1914 was found to be equipped with a camera, official interest was suddenly aroused, and the French army at once established a regular aerial photographic service, their example being followed soon after by the British and other Allies. By the end of the war, photography had become a major war activity, and tens of thousands of photographs were made every week. It is estimated that by 1918 over a million prints a month were being made and distributed.

At first, any convenient camera was held in the hand, and merely pointed over the side of the plane at the object to be photographed. However, in 1914, when the demand for aerial photographs increased by leaps and bounds for war purposes, it became apparent that special cameras were necessary. An aerial camera must be very rigid, mounted so as to be free from vibration, and prefocused for infinity but not thereafter adjustable for focus. It must be equipped with a long-focused lens to show fine detail, and at first an adjustable focal plane shutter was used as no large between-lens shutters were available. Also, the size of picture should be as large as convenient to cover a wide angular field.

Prior to about 1922, aerial photographs were invariably made on glass plates, housed in various ingenious forms of magazine or changing box holding from 6 to 50 plates at a time. At first, roll film was found to be unsatisfactory, and it was not adopted for aerial cameras until two or three years after the war had ended. The problem of the use of roll film was twofold: firstly, adequate processing equipment had to be designed to handle large rolls of film, and secondly, some means had to be found to hold the film flat during exposure. A pressure pad and glass plate have been used, but this is likely to cause scratches and static marks on the film; a much better solution was found in Folmer's introduction of a "suction back," to pull the film down against a flat perforated metal plate.[3]

The French[4] adopted from the first a focal length of 25 cm (10 inches) and a 13×18-cm plate (5×7 inch). The 10-inch focus was soon found to be too short for high flying, so cameras were constructed for 50-cm (20 inch) focus, covering an 18×24-cm plate (7×9½ inch), which became the standard focus and plate size for the French army. The speed of all these lenses was $f/4.5$. A little later, the French introduced a lens of 120-cm focal length (47.2 inches), also for the 18×24-cm plate, at an aperture of $f/6.5$, claiming that this was the longest camera in the world! This camera was not particularly popular as it occupied far too much space in the plane, and covered only a very narrow angular field. Towards the end of the war, a moderately wide-angle camera was introduced covering an 18×24-

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[1] L. P. Clerc, *Applications de la photographie aérienne*, Chap. I.

[2] D. M. Reeves, *Aerial Photography*, p. 3.

[3] U. S. Patent 1,309,798 (1919).

[4] A. H. Carlier, *La photographie aérienne* (1921) Chap. 2.

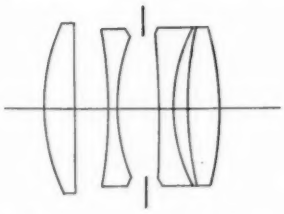

FIG. 1. Ross "Xpres." Stuart and Hasselkus, British 29,637 (1913).

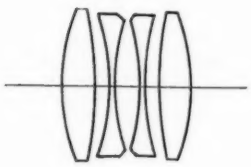

FIG. 2. The four-piece air-spaced lens (Aviar, Dogmar, Aerostigmat).

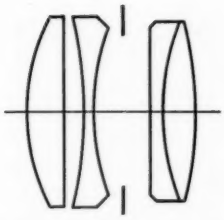

FIG. 3. The Zeiss "Tessar" lens (Rudolph, U. S. 721,240).

cm field with a 25-cm lens. This was intended for rapid reconnaissance or survey work.

The British[5] Royal Flying Corps began experiments in aerial photography as early as 1912, but progress was very slow until the war started. At that time, 4×5-inch glass plates were regarded as standard, and 8-inch or 10-inch focus lenses were used. The camera was hand-held at first, but later fastened to the outside of the fuselage of the plane. The operation of the shutter and plate changing mechanism was later made automatic, power being derived from a small air-screw mounted in front of the camera.

Eventually, cameras were designed to take interchangeable lenses of 4-, 6-, 8-, 10½-, and 20-inch focus, and the 4×5-inch negatives were enlarged before use. When the war began, no British lenses were available in sufficient quantity, and Zeiss Tessar lenses were requisitioned from their owners by the Government. Later Ross and Taylor, Taylor, and Hobson commenced manufacture of the Xpres (Fig. 1) and Aviar (Fig. 2) lenses, respectively (both $f/4.5$).

Towards the end of the war, all the Allies agreed to standardize on the 18×24-cm size (7×9½ inch) and lenses from 7-inch to 36-inch focus were used.

The German army during the last war started with the very great advantage of possessing a fully developed optical glass and lens industry. Their first aerial camera used 9×12-cm plates (3½×4½ inch), with an $f/4.5$ Tessar (Fig. 3) lens of 25-cm focus. This picture size was soon found to be too small, and it was replaced by a 13×18-cm size (5×7 inch). For this size, the standard lenses were of 25- and 50-cm focus (10 and 20 inch), with the usual glass plates and focal plane shutters. For the 25-cm size, a Zeiss Tessar $f/4.5$ lens was used and for the 50-cm size, an $f/4.8$ Triplet (Fig. 4). Later 70-cm (27½″) and 120-cm (48″) $f/7$ Triplets were adopted also. The German cameras were made by Zeiss, Goerz, Ica, and Ernemann.

The earliest use of roll film in an aerial camera was apparently the Douhet-Zollinger (Italian) camera made in 1915, and shortly after abandoned. It used an $f/3.5$ Zeiss Tessar of 10-cm focus, giving a 6×6-cm picture. The film 6 cm wide was supplied in 20-meter rolls for 300 photographs, a perforation every 6 cm along one edge of the film indicating the position of successive frames. The mechanism advanced the film and simultaneously cocked the shutter, just as in some modern types of amateur cameras.

THE USE OF LONG-FOCUS LENSES

Soon after aerial photography became a routine matter, a very interesting fact gradually emerged and became firmly established.[6] This was, that a lens of long focus using contact printing, gives better definition of fine detail in the print than a similar short-focus lens using enlargement in printing. From simple considerations, we should not expect this to be the case. The shorter-focus lens should give elementary images which are smaller than those given by the longer-focus lens, in proportion to the two focal lengths; however, if we then enlarge the image given by the shorter-focus lens in inverse proportion to its focal length, we should end up with the same size of elementary images in both.

This discrepancy is apparently due to two factors. Firstly, the enlarging lens has inevitably

[5] *Photography as a Scientific Implement* (Blackie, 1923), Chap. 10.

[6] H. E. Ives, *Airplane Photography* (1920), p. 59.

some aberrations which tend to spoil the sharpness of the image, and secondly, the graininess of the negative is magnified by the enlarging process, and it is therefore more serious with shorter-focus lenses.

An imaginary example will show how this operates. Suppose that for a low-contrast object such as would be ordinarily photographed from the air, the resolution of the emulsion is about 25 lines per mm. The resolving power of a certain 6-inch lens may be about 40 lines, and that of the corresponding 12-inch lens would, therefore, be only 20 lines. The combination of 6-inch lens and film might resolve about 16 lines, and the combination of 12-inch lens and film would resolve about 12 lines per mm. On enlarging the 6-inch image by a factor of two to give the same sized print as was obtained with the 12-inch lens, the resolution drops from 16 to only 8 lines, which is much less than that found in the unenlarged 12-inch picture.

Whatever may be its cause, this effect is well enough established to deter aerial photographers very definitely from using smaller lenses. A short-focus lens would lead to great gains in film economy, lightness and compactness of equipment, speed and efficiency of shutters, and ease in film processing; all of these advantages are now being sacrificed to obtain improved definition.

This phenomenon is familiar to users of miniature cameras, who often find that a 5-times enlargement from a $1\times1\frac{1}{2}$-inch miniature negative, taken with a 2-inch lens, is never as crisp and clean-cut as a direct contact print from a 5×7 negative made with a 10-inch lens.

DEVELOPMENTS IN THE UNITED STATES

In this country, the Brock[7] Aerial Surveying system was started in 1914, using glass plates $6\frac{1}{2}\times8\frac{1}{2}$ inches in size, with a $9\frac{1}{2}$-inch Goerz lens. The pictures were enlarged to the equivalent of a 14-inch lens before making the maps. When the United States entered the war, European lenses were not available, and it became a very grave and urgent problem to initiate and develop to an adequate capacity both the optical glass and the aerial lens industries. The optical glass story is now a matter of history, but the absence of suitable glass types greatly hampered the design and manufacture of aerial lenses to an extent scarcely realized today. As Mr. Frederick remarked in his paper read before this Society in 1919,[8] "We were confronted with the problem of making a lens out of very unsuitable materials, a problem not unlike that of making something out of nothing, and altogether discouraging to contemplate." Finally, when a supply of barium crown glass was promised, the design of an $f/4.5$ lens of $8\frac{1}{2}$-inch focus (later raised to 10 inches) was completed, to cover a 4×5-picture, similar to the lenses used regularly by the British.

While the $f/4.5$ lens was being designed, a 20-inch $f/6$ lens was required, and both designs were completed almost together. These lenses were the only ones to go into regular production by Eastman Kodak Company before the war ended in November, 1918. A 48-inch $f/7.7$ lens was planned, and would have been manufactured had the war continued. These three Eastman lenses were all of the 4-piece airspaced type (Fig. 2) made from dense barium crown and barium flint glasses of approximately the same index.

In designing a special lens for aviation purposes, advantage may be taken of the unusually narrow angular field generally employed. Care must be taken too to overcorrect the lens chromatically to a slight extent, since almost all aerial photography is performed with panchromatic film and a blue-absorbing filter.

DEVELOPMENTS SINCE 1918

As soon as the war was over in 1918, the great rush to produce aerial lenses subsided, and designers had time to study the situation and endeavor to stabilize it. From that time three quite distinct trends have appeared, namely: (a) lenses for military reconnaissance and pictorial purposes, (b) lenses of high aperture for night

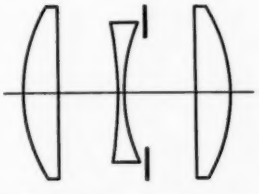

FIG. 4. The Triplet type of construction.

[7] J. Opt. Soc. Am. **22**, 111 (1932).

[8] J. Opt. Soc. Am. **2**, 34 (1919).

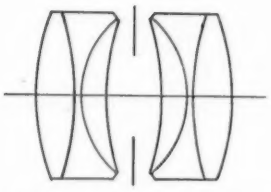

FIG. 5a. The Goerz "Dagor" lens, German Patent 74,437 (1892).

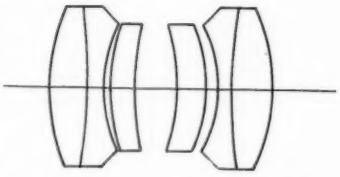

FIG. 5b. Zeiss "Orthometar," Merté, U. S. 1,792,917 (1931); Ross "Wide-angle Xpres." Hasselkus and Richmond U. S. 1,777,262, (1930).

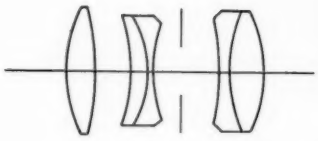

FIG. 6. Eastman Kodak 13½-inch $f/3.5$ aviation lens. Altman, U. S. 1,880,394 (1932).

photography, and (c) wide-angle lenses for aerial surveying. Some signs of these distinctions were appearing even during the war, but after it was over, the separation rapidly became very marked.

(a) Military Reconnaissance Lenses

From the early Eastman and Folmer cameras, great strides have been made in the United States, notably by the Fairchild Corporation, in both the hand-held 4×5- and 5×7-types, and the automatic roll-film 7×9- and 9×18-inch cameras with suction back. The 7×9-size remained standard until about 1935 when it became gradually replaced by the 9×9-inch size. The 9×18-inch size has not been particularly popular, for some reason. The Fairchild cameras at first used focal plane shutters, but later they developed a very large between-lens shutter which has been much used.

For these cameras during the last 20 years, the standard focal lengths and apertures have been somewhat as in Table I. A few other odd sizes have been used occasionally, such as 5×5 inch and 5½×6. Practically all the lenses used have been of the Tessar type, comprising a pair of airspaced elements ahead of the stop, and a cemented pair behind. The principal manufacturers have been Zeiss (Tessar, Fig. 3), Goerz (Dagor (Fig. 5a), Dogmar (Fig. 2), and Aerotar), Schneider (Xenar, Fig. 3), Eastman Aerostigmat (Figs. 3 and 6), Bausch and Lomb (Tessar, Fig. 3), Dallmeyer (40-inch Telephoto, Fig. 7), Taylor-Hobson (Cooke, Fig. 4), and Ross (Xpres, Fig. 1). During the present war, thousands of aerial lenses of many sizes and types are already being manufactured in the U. S. A. from domestic glass, a situation in strong contrast to that obtaining during the war of 1914–18.

Just as in 1914–18, the present war is causing a very rapid development in the art of taking military photographs from the air. With anti-aircraft fire reaching almost to 40,000 feet, a reconnaissance plane must either fly above that height, or the flier must hide in the clouds until over his objective, and then dive down to snatch a picture before being hit.

The first of these alternatives requires a long-focused lens such as the 40-inch $f/8$ telephoto now being manufactured in this country, together with a red or infra-red filter to penetrate atmospheric haze. It is interesting to note that in 1914, the usual height for aerial photography was 3000 or 4000 feet, and that by the end of the war

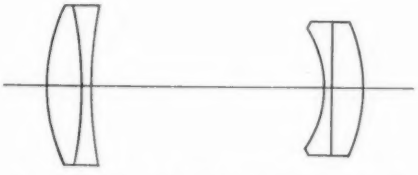

FIG. 7. A typical Telephoto lens (Booth, U. S. 1,480,929).

TABLE I.

Size (Inch)	Speed	Focus (Inch)	Corresponding Angular Semi-Field
4×5	$f/4.5$	6¾	26°
5×7	$f/4.5$	9½ or 10	24°
"	$f/5.6$	20	12° Regular and Telephoto
"	$f/8$	40	6° Telephoto
7×9	$f/4.5$	10	30°
"	$f/5$	12	26°
"	$f/4.5$	20	16°
9×9	$f/4.5$	12	28°
(or 8×10)	$f/3.5$	13½	25°
"	$f/6.3$	14	24°
"	$f/6$	24	15°
9×18	$f/6$	24	23°

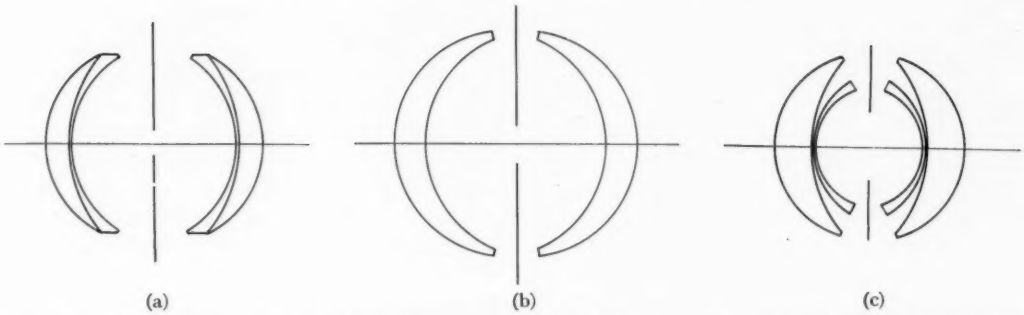

FIG. 8 a. Busch's "Pantoskop" lens, $f/30$, 45° (1865). b. Von Höegh's "Hypergon" lens, $f/30$, 67° D.R.P. 126,500 (1900). c. Richter's "Topogon" lens, $f/6.3$, 45° D.R.P. 636,167 (1936).

reconnaissance planes were forced up as high as 18,000 feet.

For the second alternative, a number of small, fully automatic cameras have been developed in Europe, one example being a focal plane camera utilizing a 5×5-inch film between a glass plate and a pressure pad, with an assortment of interchangeable lenses. This camera is intended to be carried in the tail of a small plane and operated entirely by remote control.

(b) Night-Photo Lenses

Towards the close of the World War, some experiments were made in night photography from the air, using a flash-bomb dropped from the plane. The method was to use a flash of very short duration (1/100 second) and hold the camera shutter open until the picture was taken. In Dr. Ives' book,[9] written in 1920, he predicted that longer flashes would probably be used, with some arrangement to synchronize the opening of the shutter with the peak of the flash. Even trailing the flash bomb on the end of a long wire had been considered, but dismissed as impractical!

Within the last few years Colonel G. W. Goddard of the U. S. Army Air Corps has developed a satisfactory photo-cell synchronization device by which excellent night flash photos have been obtained using an Eastman 13½-inch $f/3.5$ lens (Fig. 6). Progress in night photography is most necessary and will assuredly come both in the direction of brighter flash-bombs, and by the use of faster films and lenses.

[9] Reference 6, p. 387.

(c) Lenses For Aerial Surveying

In the early days of aerial photography, the same lenses were used for reconnaissance work and for map-making. It was, therefore, necessary to correct the distortion particularly well. Since the war, however, the needs of the map-maker have received a great amount of attention, and a number of special distortionless wide-angle lenses have been designed and manufactured for this purpose.

One of the first of these was the Goerz Aerotar, a modification of the well-known Dagor (Fig. 5a), working at $f/6.8$, covering a 5½×6-inch picture at 6 inches focal length. This corresponds to an extreme half-angle of view of 34°.

Within a few years, a focal length of 8¼ inches became standardized for a 7×9-inch picture, corresponding to a corner angle of 34½°. At first lenses such as the $f/6.8$ Dagor were used for this, but around 1930 appeared the Zeiss "Orthometar," and the very similar Ross "Wide-angle Xpres" (Fig. 5b), both working at $f/4$. These two lenses are really a modification of the Dagor, obtained by separating the inner positive meniscus elements from the cemented triplets, and "bending" them to a somewhat weaker shape. The outer doublet members have a very weak negative power, so the whole system can, in a sense, be regarded as a modified periscopic lens, the inner lenses constituting the periscopic part, the outer components being practically afocal correcting lenses to remove the aberration residuals of the positive elements. The field of this lens is satisfactory to almost 35° at $f/4$, and quite distortionless.

These lenses represented the ultimate in aerial survey lenses until the Zeiss "Topogon" $f/6.3$ lens (Fig. 8c), covering a half angle of 45° was designed by Richter in 1933. A 6-inch lens of this type covers successfully to the corners of a 9×9-inch picture. It is also made in this country by Bausch and Lomb, as the "Metrogon" lens. A sample in the 12-inch size has been made to cover an 18-inch square picture, but this very large size seems likely not to be used extensively because of the size and weight of the camera, and the difficulties of handling this large film. Ross in England have made a slight modification of the Topogon lens, known as the $f/5.6$ Wide-angle Survey lens, by dividing the rear positive element into two airspaced elements.

As can be seen from the diagram in Fig. 8, the Topogon lens is of an extreme meniscus type of construction, being probably descended from the old Harrison "Globe lens," or the Busch "Pantoskop," making use of the teaching given us by Von Höegh in the Goerz Hypergon. The deep meniscus form of the Hypergon leads to a perfectly flat field out to 67° from the lens axis, but as it is uncorrected for chromatic and spherical aberration, its useful aperture is limited to about $f/30$ or less. The Pantoskop was achromatic but not spherically corrected, its aperture being likewise limited to about $f/30$. In Richter's design he has separated the positive and negative elements of the Pantoskop lens, and given the negative elements a "bending" to a deeper meniscus shape. In this way, sufficient degrees of freedom are made available to correct the aberrations at $f/6$, over a semi-field of about 45°. At this very wide angle, the illumination is naturally rather low, but the lens is quite satisfactory in practice.

A high lens speed is of almost no importance to the peace-time mapping photographer, because he flies only in perfect weather. However, extreme angular fields are very desirable, and now that a 45° field is available, he will never be satisfied with less.

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Optics in Sabotage and Espionage*

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THE maintenance of our national defense and the preservation of our internal security have increased the quantity of work that is being performed by the scientific crime detection laboratory of the Federal Bureau of Investigation in Washington, D. C. To meet the increase and influx of investigations arising from sabotage and espionage activities, the laboratory has available numerous pieces of equipment and precision instruments that will aid in the advancement of this purpose. The laboratory of the Federal Bureau of Investigation, being a service organization, offering assistance willingly in all matters involving scientific crime detection, presents itself to the cause of doing all in its power to analyze and solve, limit and prevent any criminal activities which are injurious to this country's internal security.

The laboratory staff is made up of many men, each one a specialist in a particular branch of science. The forensic applications of petrography, metallurgy, chemistry, serology, toxicology, spectrography, physics, firearms identification, and document identification are numerous, and they form the basis of the work of the laboratory specialists in the respective fields. Needless to say, optical equipment is not found lacking. Optical instruments are probably used more frequently than any other type of instrument. Optical instruments, because of their ability to reveal characteristics minute in size and many times significant in nature from the standpoint of criminal work, and to expose other charac-

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teristics which cannot be observed with the human eye and which cannot be detected by equipment of another nature, are a necessity in a scientific crime detection laboratory. As an example, the Federal Bureau of Investigation crime detection laboratory in recent years has been equipped with some of the most modern developments in the optical field, such as the spectrograph, the densitometer, and high powered magnifying equipment.

The petrographer, for example, using the petrographic microscope, which is equipped with a universal stage for mounting and observing the specimen and which is provided with an auxiliary source of polarized light, determines the optical characteristics of soils, minerals, dirt and débris. The refractive properties, the axial properties of crystals, the polarizing properties, the crystalline form, if any, and the cleavage of the substance being examined—all of these characteristics can be determined optically. Consequently, in scientific criminal examinations of this type, in which comparisons of samples are desired, a great significance is attributed to the optical characteristics which are observed by the petrographer. Many times, accurate measurements relative to the indices of refraction of particles of soil, crystals, minerals, or glass are extremely pertinent. To assure high accuracy in this type of analysis, a double variation method of determining the index of refraction is employed. The double variation method makes use of two methods of varying the index of a liquid, namely by changing the temperature of the oil and by changing the wave-length of the light used as an illuminating source. Therefore, if a crystal or a particular piece of glass, submitted as evidence, is to be examined in order to compare it with other specimens or simply to determine its index of refraction for identification purposes, the double variation method is applied and accurate determinations of the indices of the crystal or of the glass can be made.

In many petrographic cases, specimens of oils and grease are submitted for examination in order to determine if there are any foreign materials or abrasives present. The oil cup with the oil contained therein or the catch-pan from a disrupted piece of machinery might be submitted for investigation. The foreign materials present are first separated from the oil by centrifuging, and then the residue is analyzed to determine the abrasive nature of the material. The abrasives recovered may be compared with known abrasives maintained for comparison purposes in the laboratory or with abrasives obtained from particular sources in the plant or in the immediate neighborhood of the disrupted machine. By this method oftentimes it is possible to localize the source of the contamination and the destruction. Consequently, the petrographer finds innumerable applications of optics in his particular field.

Metallurgy also figures significantly in the analysis of cases involving sabotage and suspected sabotage. Evidence which is concerned with the disruption of machinery by fracturing vitally important equipment or machine parts, with the dismembering of wire cables, etc., to cause failure and fracture of the cable when a strain is placed upon it, with the effect produced by the existence of metallic fragments of a foreign nature in lubricating systems, bearings and other moving parts of machinery—examinations of this type receive the scientific consideration of the metallurgist. To analyze metallurgically a particular specimen and to compare it with other specimens which may lead to the uncovering of the saboteur or saboteurs, cross sections and longitudinal sections of the specimens are mounted so that their crystalline structures may be observed. The sectional mountings when observed with the metallurgical microscope, employing vertical illumination, usually will reveal the similarity or dissimilarity between the specimens that are being compared. Also the nature of the industrial treatments which were initially employed in the manufacture of the specimen as well as the functions, principally the stresses and strains, that the specimen was made to perform as a component part of a machine, may be evident to the metallurgist after an examination of the characteristics of the sectional mountings.

A case arises in my mind which depicts the representative type of work that this section is doing in national defense. A tractor which was manufactured in a plant in the Midwest was exported to Melbourne, Australia. When it was received in that city a large deposit of fine iron

granules was found in the oil pan. It was stated that the tractor's timing gear, crankshaft, and bearings had been ruined by the granules, and it was believed that an act of sabotage had been committed. A quantity of similar iron granules was discovered around the oil level gauge sleeve of the tractor, adhering under paint which had hardened. Inasmuch as the paint was applied in the United States, these granules must have been present prior to the exportation of the tractor. The tractor in question was valued at $5000 and was of the type which some foreign governments, principally Great Britain and Australia, have converted into armored tanks for military purposes. A metallurgical examination was made, and the samples were revealed to be white cast iron. The polished sections of the above specimens revealed them to be composed of cementite and pearlite with no graphite plates such as occur in gray cast iron. White cast iron is extremely hard and brittle. Because of this hardness, it was suggested that it may possibly be used as an abrasive. Further investigations were carried out in this country following on leads revealed by the laboratory examination.

The metallurgical section of the laboratory often works in conjunction with another section, namely, the spectrographic section. This section is equipped with several microscopes with auxiliary oculars and objectives to control the desired magnification of the specimens, a medium quartz spectrograph, an absorption spectrograph, a comparator micrometer, and a comparator-densitometer. In the last decade, it has become evident in the laboratory that many advantages might arise, with regard to crime and its scientific detection, if informative and accurate analyses of paint samples, usually minute in size, could be performed. These examinations are carried out almost exclusively by the spectrographic section of the laboratory, and they constitute probably one of the most numerous examinations conducted spectrographically. However, it should be pointed out that many other types of metallic specimens are examined by this section parallel to and in conjunction with a metallurgical examination or a tool marks' examination. A tool marks' examination is an examination in which an attempt is made to affirm or deny that a particular tool mark, for example, a jimmy mark on a window frame, was produced by a particular tool or in the example referred to, a particular jimmy. A spectrographic examination of any material adhering to the tool is made to determine if it is or is not similar to the material or painted object which was marked. Or then again, burrs or loose metallic particles from the tool may be deposited on the marked object, and in this case the deposited metal and the metal of the tool are compared spectrographically.

The primary advantages of the spectrographic method over other non-optical methods are: first, that only a very small sample of the evidence is used, the remainder being available for court presentation; second, that the examination can be carried out with great speed and accuracy; third, that the instrument is so sensitive that elements and impurities present in extremely small quantities are readily detectable; fourth, that a complete record of the material burned is registered on the photographic plate and also that this photograph is admissible as evidence in a court of law.

The spectrograph was employed a short time ago in the analysis of some 176 hacksaw blades submitted as evidence involved in damage to a Navy experimental aeroplane in the Curtiss Aeroplane Division, New York. Submitted along with these blades was one forty-five degree, one-inch hose ell aluminum alloy fitting which was used in the direct feeding unit from the ship's gasoline tanks to the carburetor. During the assembling of the flight motor of this plane, it was discovered that this fitting had been tampered with. A hacksaw blade had apparently been used to cut the seventh thread of the fitting for the purpose of weakening its tensile strength and to cause serious damage to the ship either before or after it was placed into flight. There were also forwarded to the laboratory numerous hacksaw blades which were secured from the employees in the experimental section of the plant. A spectrographic examination of the teeth of these blades limited the search for the destructive blade from 176 to 17 blades. Seventeen of the blades spectrographically were shown to have elements on them which were similar to the elements in the aluminum alloy fitting which had been tampered with. This

limitation of hacksaw blades and suspects significantly simplified the criminal investigation.

Another interesting case that was handled spectrographically was the case of the wreck of a streamliner passenger train. This train was proceeding westward and the point of derailment was just east of a steel girder bridge over a river. The members of the train and field crews advised that they saw nothing unusual along the tracks in that vicinity. Following the wreck, it was observed that one of the rails had been bent in, and spiked in that position. This bent rail was then painted to disguise the bent section when the train approached the break in the rail. Because it was night and the light on the front of the train was on, the reflection from the bright steel rails would ordinarily have indicated to the engineer that the track was displaced from its proper path. The reflection from that section of the rail was removed by painting the rail, and indications of the displaced rail were not apparent. A claw bar, spike maul, track wrench, jack handle, a small roll of wire, and two zipper jackets were found in the bottom of a five-foot water hole, approximately 900 feet from the bridge. In the opinion of experienced railroad men this act was committed by men experienced in this type of work. Their opinion was based on the location selected for the derailment, on the fact that the derailer was arranged on the outside of the curve, and on the fact that the rail displacement was effected in such a manner so as not to interfere with the operation of an automatic block signal in that vicinity. Subsequently, a cap from a paint can was found at the scene, and this was also submitted to the laboratory. Spectrographically it was possible to state that the paint removed from the track, the smears of paint on the zipper jackets, and the paint on the paint can cover were all similar in composition. A comparison was made with some known paint samples submitted by the Con-Ferro Paint and Varnish Company, St. Louis, Missouri, and this paint was revealed as being similar in color and composition to the paint previously submitted. However, the company's record did not indicate that this can of paint had been sold in the locality of the wreck. All efforts to trace the buyer of such a can of paint have failed, and photographs of the two zipper jackets were printed and exhibited in post offices throughout the country with the request that any person knowing the owner or owners of the jackets furnish that information to interested authorities. The interesting point about the case is the success encountered with the spectrograph in the analysis of paint specimens even though the sample is extremely small, as was the sample removed from the two jackets. It is also pointed out that if at any time paint specimens possess definite layer structures, photomicrographs and photographic comparisons of the sequence of colors are made on color film.

Since destruction to person and property can be committed in innumerable ways, one can appreciate that many cases arise which require the specific attention of an expert in chemistry, toxicology or serology. Although cases which are considered by the toxicological and serological sections of the laboratory are not usually concerned with national defense, it is pointed out as a matter of interest only, that these sections utilize the optical equipment in the laboratory whenever the specific occasion demands it. The serological section has occasion to use its micro-spectrophotometer routinely in the identification of blood by the observation of the absorption bands of oxyhemoglobin.

The chemist, or more specifically the microchemist, finds the binocular microscope a necessity in investigations dealing with sabotage and espionage. The microchemist, when working with small bits of evidence, many times must observe the chemical and colorimetric tests being performed under the microscope. Furthermore, the application of colorimetry is in itself an extensive and important application of optics in forensic chemistry.

Probably one of the most interesting types of chemical cases, which have risen in importance with the increase of sabotage and espionage activities in this country, is the case involving destruction caused by spilling or placing acids or other destructive chemicals in or on equipment being produced under the defense program. To determine the chemical employed and to observe the nature of the surface destruction as well as to make sample tests with suspected chemicals while in the process of their destruction, requires

unlimited effort and acute and persistent observation under the microscope. Much success has been encountered along these lines, and it is evident that this success is due in great part to the optical equipment which facilitates the work of the specialist.

Much more directly concerned with the general topic of this paper are the work and investigations which are carried on in the firearms section of the laboratory. National defense work is an important phase of the work of these specialists, and consequently it receives expeditious attention, utilizing at all time equipment which is available and necessary. Several comparison microscopes are at hand for visual work or for making photographs for record purposes. Also several wide-field binocular microscopes, which are extremely useful for the examination of bullets, powders, cartridge cases, and the like, are available. The most recent addition to the equipment of the firearms section is a toolmaker's microscope for the accurate measurement of striations, depressions, and scratches on bullets and cartridge cases as well as for the applications that it will have in tool marks' examinations.

The document section and a subdivision of it which has developed enormously since the defense emergency, namely, the cryptographic section of the Federal Bureau of Investigation laboratory, is engrossed with the task of comparing and analyzing documents, checks, codes, and ciphers. This particular group finds incessant applications of the simple magnifier and microscope and also the opacimeter for paper comparisons. The search for fluorescent invisible writing using ultraviolet light and the use of ultraviolet and infra-red photography for the restoration of secret and obliterated writing, are parts of their extensive field.

By this time the absence of references to particular cases and examples may be becoming quite obvious; but it must be realized that because of the nature of the crimes being considered, it is not advisable to be specific lest the method and manner of scientific crime detection be generally revealed and its effectiveness stunted. It is hoped that this paper has served to illustrate in some small measure the type of work that is being done by the technical laboratory of the Federal Bureau of Investigation, especially with regard to optics, not overlooking, however, many other fields of endeavor which are utilized therein. It may be of interest to you to know that during the month of September, 1941, 1548 more scientific examinations were performed than in the same period of the previous year. This figure indicates an increase of 282 percent in the number of examinations made.

It was in 1932 that Mr. Hoover, as part of his long-range program for developing the efficacy of the FBI, initiated the crime detection laboratory. At that time there was considerable skepticism among some police officials as to the practical value of applying laboratory methods to criminal investigations. Mr. Hoover's foresight in this respect has since been well proved. In 1937, determined to afford police investigators of the nation the best staffed and best equipped laboratory possible, the Director sent Mr. Coffey, who is presently in charge of the laboratory, to Europe where he studied the various scientific police facilities of foreign nations. He reported back that American equipment and scientific personnel were equal to or superior to those in the great criminological centers of Europe.

Today the FBI's laboratory staff numbers sixty-five scientists, and its equipment is the best in the world for the purposes used. Over 2000 analyses are made each month, and its technical services are available without cost to the police of the nation.

The "Diffusing Effect" of Fog*

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(Received November 5, 1941)

I. INTRODUCTION

THERE seems to be some doubt whether the edge of a dark object, seen against the sky in a fog, is made to appear diffuse by the fog, or whether it remains sharp, the fog serving merely to reduce the contrast between the object and the sky. The question is of some importance in the theory[1] of the visual range in fog, since it has been shown that the threshold of contrast is affected by the sharpness of the boundary between the two fields.[2] Bennett[3] believed that this diffusing effect was one of the main factors limiting the visual range in fog; others have doubted this; and since the difficult experiments necessary to settle the question do not seem to have been made, it may be of interest to calculate what might be expected under simple, but not unduly restrictive, assumptions about the shape and position of the dark object.

In the interests of a reasonable brevity, it must be assumed that the reader is acquainted with the general theory[1] of the apparent brightness of distant objects. Here we shall state only the special assumptions necessary to make our present problem susceptible to analysis.

II. GEOMETRICAL AND PHYSICAL ASSUMPTIONS

What we have to calculate is the apparent brightness of a dark object, standing above the horizon in a fog at some distance less than the visual range, at a number of points near the geometrical edge and along a line at right angles to it. For convenience, we shall consider a black object with a straight, horizontal upper edge, rising a degree or so above the horizon, and several times as long as it is high. The points in question will all lie within a few minutes of angle of the edge.

Let the observer be at O (Fig. 1), and let his horizon be represented by the circle $ABCDA$. Let $EFGH$ be the black object referred to, and let it be at a distance s from O. Let P be one of the points, near the edge, at which the apparent brightness is to be calculated, and let us suppose that it is not far from the middle of the upper edge of the object.

The following physical assumptions, with two exceptions, are those commonly made in theoretical work on the visual range, and are not especially restrictive:

(a) The extinction coefficient is constant throughout the pyramid of air between the observer and the object, and in the general direction of the object as far as the horizon. Its value is σ (km^{-1}).

(b) The light scattered in a given direction from an element of volume of the atmosphere may be considered as coming from a point source of which the intensity is proportional to the elementary volume.

(c) The light rays may be considered as rectilinear, atmospheric refraction being neglected.

(d) The height of the black object is small in comparison with its distance from the observer.

(e) The earth is considered as plane and horizontal. (As the visual range in fog is never more than a few hundred meters, this is not a serious limitation.)

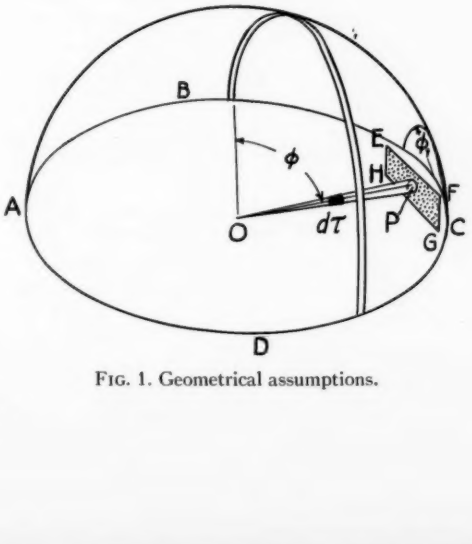

FIG. 1. Geometrical assumptions.

* Published by permission of the Controller of Meteorological Services, Department of Transport, Canada.

[1] For a general summary see W. E. K. Middleton, *Visibility in Meteorology* (University of Toronto Press, 1941), second edition.

[2] W. E. K. Middleton, J. Opt. Soc. Am. **27**, 112–116 (1937).

[3] M. G. Bennett, Q. J. Roy. Met. Soc. **56**, 1–29 (1930).

(f) The albedo of the earth is assumed to be zero.

(g) Multiple scattering is neglected.

(h) The sky is uniformly bright, its brightness being denoted by B. This assumption is a close approximation to reality under an overcast sky.

We shall not attempt to justify assumptions (f) and (g) until the analysis has been presented, when it will be shown that they do not invalidate the results obtained.

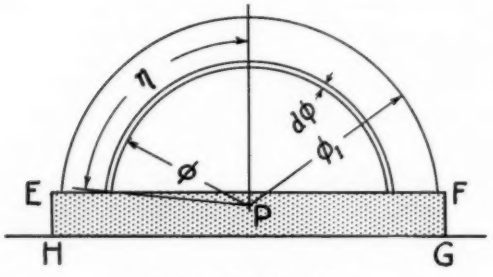

FIG. 2. Calculation of η.

III. THE APPARENT BRIGHTNESS OF A POINT IN THE OBJECT

Referring to Fig. 1, consider a cone of air with its apex at O and its axis directed towards a point P in the object. Let the cone comprise a small solid angle df, and consider an elementary volume

$$d\tau = r^2 dr df$$

cut from the cone by two planes $r=r_1$ and $r=r_1+dr$, OP being parallel to the axis of r. The elementary volume will be illuminated by the entire hemisphere of sky, with the exception of the part cut off by $EFGH$. A certain portion of the flux scattered in all directions by $d\tau$ will be directed towards the pupil of the eye at O; this will be proportional to the luminous intensity of $d\tau$ (considered as a point source by assumption (b) above) in the direction PO, and to the solid angle

$$d\omega = ds/r_1^2$$

subtended at $d\tau$ by the pupil of area ds. Since σ is constant, this intensity will be proportional to the volume $d\tau$ and to a scattering function $\sigma \cdot l(\phi)$.

For convenience of calculation, we may divide the sky as seen from $d\tau$ into two parts by a small circle at a constant angle ϕ_1 from the pole of OP. For the volume elements close to P, this constancy of ϕ_1 is equivalent to neglecting the fact that the extremities of the object $EFGH$ cut off the illumination from a small part of the sky. If ϕ_1 is of the order of 10°, however, the effect of this will be almost independent of the position of P with respect to the upper edge of the object.

(a) The Portion of the Sky Corresponding to $\phi_1 < \phi < \pi$

The illumination of $d\tau$ from a zone of angular width $d\phi$ is

$$dE_\phi' = B\pi \sin\phi \, d\phi \tag{1}$$

the angle ϕ being measured from the pole of OP. A certain amount of the flux from the zone $d\phi$ will be scattered in the direction PO towards the eye; this will be

$$dF_\phi' = B\pi \sin\phi \, d\phi \cdot d\omega d\tau \cdot \sigma \cdot l(\phi); \tag{2}$$

and of this an amount

$$dF_\phi = B\pi \sin\phi \cdot d\omega d\tau \cdot \sigma \cdot l(\phi) e^{-\sigma r} d\phi \tag{3}$$

will reach the eye, taking into account the attenuation by the foggy air. Writing out the expressions for $d\omega$ and $d\tau$ this becomes

$$dF_\phi = B\pi \sin\phi \cdot ds \cdot dr \cdot df \cdot \sigma \cdot l(\phi) e^{-\sigma r} d\phi. \tag{4}$$

Hence the illumination produced at the eye by light scattered from this zone is

$$dE_\phi = B\pi \sin\phi \cdot df \cdot \sigma \cdot l(\phi) e^{-\sigma r} dr d\phi \tag{5}$$

and the brightness of the volume element $d\tau$ in the direction PO, due to light from the zone $d\phi$, is

$$dB_1 = B\pi \sin\phi \cdot \sigma \cdot l(\phi) e^{-\sigma r} dr d\phi. \tag{6}$$[4]

A double integration now gives us the total apparent brightness B_1 of the surface of the black object near P, due to light from this portion of the sky:

$$B_1 = B\pi \int_{\phi_1}^{\pi} \int_0^a l(\phi) \sin\phi \cdot \sigma e^{-\sigma r} dr d\phi, \tag{7}$$

[4] The relations between flux, illumination, and brightness that are implied in the above are clarified by the adoption of the modern definition of *brightness* due to A. Gershun, J. Math. Phys. **18**, 51–151 (1939), p. 61: "The brightness of a luminous source may be defined as the normal component of illumination produced by that source per unit solid angle."

which reduces to

$$B_1 = B\pi(1-\epsilon^{-\sigma s})\int_{\phi_1}^{\pi} l(\phi)\sin\phi\, d\phi. \qquad (8)$$

Since $l(\phi)$ is in general not analytic, this integration must be performed graphically.

(b) The Portion of the Sky Corresponding to $0<\phi<\phi_1$

Let the element of surface considered be at an angle θ below the top edge of the object as seen from O (see Fig. 2). Then as seen from the volume element $d\tau$ it will appear to be at an angle

$$\psi = \theta s/(s-r).$$

A zone of the sky having a width $d\phi$ will extend for an angle η on each side of the vertical, so that it will subtend a solid angle

$$d\Omega = 2\eta\sin\phi\, d\phi$$

and the illumination of $d\tau$ from it will be

$$dE_\phi' = B\cdot 2\eta\sin\phi\, d\phi. \qquad (9)$$

But $\eta = \cos^{-1}(\psi/\phi) = \cos^{-1}[s\theta/(s-r)\phi]$, subject to the limitation that $0<\eta<\pi/2$, and therefore

$$dE_\phi' = B\cdot 2\cos^{-1}[s\theta/(s-r)\phi]\sin\phi\, d\phi. \qquad (10)$$

By an argument similar to that of the previous section, we may derive an expression for the apparent brightness B_2 due to light from this part of the sky, as follows:

$$B_2 = 2B\int_{\theta}^{\phi_1}\int_{0}^{s}\cos^{-1}\frac{s\theta}{(s-r)\phi}\cdot l(\phi)\sin\phi\cdot\sigma e^{-\sigma r}dr\,d\phi. \qquad (11)$$

Unfortunately, this involves a tedious graphical double integration.

The total brightness of the object is, of course, B_1+B_2, and this may be calculated for a number of points close to the edge of the object.

IV. THE FUNCTION $l(\phi)$

The scattering function for fog droplets was calculated many years ago by C. Wiener;[5] and while there may be some reason to doubt the accuracy of his figures, the general form of the function is most probably much as he found it. The function is characterized by a very large preponderance of forward scattering (Fig. 3); and it is this fact that gives point to the present investigation.

If the sum

$$\sum_{0}^{180} l(\phi)\sin\phi$$

is calculated directly from Wiener's table, the value 28.8162 is obtained. The proper set of values for our purpose may be arrived at as follows: putting $s=\infty$ in an equation

$$B_s = B\pi(1-\epsilon^{-\sigma s})\int_{0}^{\pi} l(\phi)\sin\phi d\phi \qquad (12)$$

similar to (8), but including the entire sky, we obtain the identity

$$B = B\pi\int_{0}^{\pi} l(\phi)\sin\phi d\phi. \qquad (13)$$

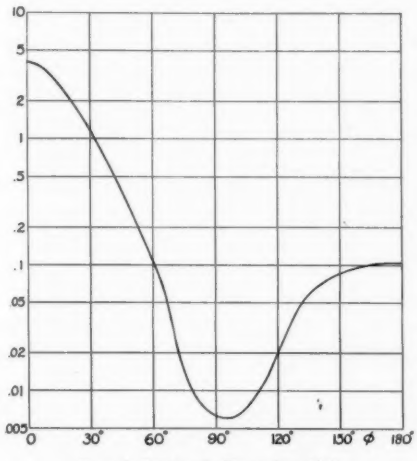

FIG. 3. Wiener's Function $l(\phi)$.

Instead of the integral let us write the sign of summation, and take the constant increment of ϕ (1°, or 0.01745 radian) outside; then

$$1 = 0.01745\pi\sum_{0}^{180} l(\phi)\sin\phi$$

and therefore

$$\sum_{0}^{180} l(\phi)\sin\phi = 18.238. \qquad (14)$$

[5] C. Wiener, Nova Acta d. k. Leop. Carol. Akad. d. Naturf. Halle **73**, 1–240 (1900); and **91**, 1–292 (1909).

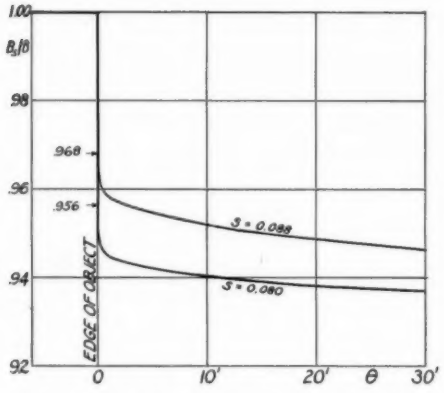

FIG. 4. Distribution of brightness across the edge of the object in a fog permitting a visual range of 0.1 km.

Thus we must multiply Wiener's values by $18.238/28.816 = 0.6329$.

V. NUMERICAL RESULTS

The evaluation of the integral in Eq. (11) is very tedious, and in view of the nature of the first results obtained, there seemed to be no reason to multiply examples. The hypothetical fog chosen for investigation was one having an extinction coefficient $\sigma = 39.1$ km^{-1}; in such a fog the visual range would be 0.1 km on the common assumption that the contrast threshold of the observer is 0.02. In such a fog let us suppose a black object (Fig. 1) at a distance of 0.08 km from the observer, and hence still visible, though not showing up very clearly against the sky behind. The reader is asked to consider whether such a set of circumstances does not seem well designed to show up any "diffusing effect" that the fog might have.

The equations were integrated mechanically for various values of θ ranging from 1 to 30 minutes of arc. For $\theta = 0$, Eqs. (7) and (11) add to give the well-known expression for the brightness B_s of a black object:

$$B_s = B(1 - \epsilon^{-\sigma s})$$

and in this case $B_s = 0.9562B$.

A brightness profile of the edge of the object and the neighboring sky is shown in the lower curve of Fig. 4, and in the upper curve are shown the results of a similar calculation, but with the object at 0.088 km from the observer. The brightness of the sky is represented by the horizontal line at $B_s/B = 1.00$, and at the geometrical edge of the object the brightness suddenly falls to the values noted on the figure, with a further decrease away from the edge.

These results are unchanged if the visual range and the distance of the object are increased or decreased in the same ratio. They are therefore representative of a large and common set of conditions in fog.

By no stretch of the imagination can such a field of brightness be called a "diffuse boundary," in the sense used by Bennett[5] or by the author.[2] The change from one brightness to the other, across the edge, is nearly complete in one minute of arc; the total change in the next half degree is less than the contrast threshold for a sharp boundary, and would almost certainly be inappreciable to the eye. Some other reason must be found for the high threshold of contrast necessary to reconcile observations in fog[6] with the theory of the visual range.

VI. DISCUSSION OF THE PHYSICAL ASSUMPTIONS

Of all the assumptions in paragraph II, the only ones that need comment are (f) and (g). The assumption of a black earth greatly facilitates the calculation. If, however, we assume the surface to have a finite albedo, the effect will be to add a certain flux incident on the element of volume $d\tau$ to that given by Eq. (1). Because of the great horizontal extent of the earth, the flux density from it in a given direction is independent of the distance from the surface, except for the effect of extinction. Hence the effect of the finite albedo of the earth will be to add a constant fraction of the apparent brightness to both the object and the adjacent sky, and therefore, at least to a first approximation, the form of the field of brightness should remain the same.

With regard to multiple scattering, the assumption of a constant and uniform brightness for the sky really takes care of the matter, except for the small portion of the total radiation that may be scattered (a) out of the cone OP, from another part of the atmosphere, and into OP again, or (b) from the earth into the cone OP by way of other parts of the atmosphere. The latter

[6] H. G. Houghton, J. Aer. Sci. **6**, 408–411 (1939).

contribution is of course zero if assumption (f) be adopted; but at least it seems unlikely that either portion could seriously alter the general brightness pattern.

The shape chosen for the object admittedly has no special virtue except to make the problem more tractable. However, it is a common shape that may occur, as a wall or a low building, for example, rising above the horizon. Since it was assumed that the sky is uniformly bright, it seems likely that an object of almost any shape, as long as it is not too narrow, will have a similar distribution of brightness across its edge, though there will be a special situation at a corner.

Experimental verification of these conclusions would be welcome.

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An Optical Unit for Obtaining Variable Magnification in Ophthalmic Use*

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(Received November 26, 1941)

THE work of the Department of Research in Physiological Optics at Dartmouth College, now enlarged to the Dartmouth Eye Institute, has been concerned with the many aspects of the problem: What are the relationships between differences in the size and shape of the ocular images of the two eyes and binocular vision and space perception? In nearly every phase of the research, lenses were necessary with which the size of the image of one eye could be altered not only in an over-all or spherical sense, but also in one meridian only. For this purpose a series of afocal-type lenses, "size lenses,"[1] were used, which increased the size of the image in steps of $\frac{1}{4}$ percent up to 2 percent and in steps of $\frac{1}{2}$ percent to 5 percent. These lenses, while satisfactory in general, do have disadvantages in many situations, owing primarily to the limitations of the fixed steps.

There was a need, therefore, for an optical device with which the size of the image in one eye could be changed continuously over the range covered by the trial case of size lenses. Such a unit would have to be light in weight, yet sturdy, simple in operation and small enough so that two units could be used together before an eye. Insofar as could be ascertained, no such device had been designed previously. Such devices as the "anamorphosers" frequently used in commercial photography, and even those used in visual acuity meters, were unsuitable, being much too cumbersome and usually requiring precision mechanical cams. The problem was solved satisfactorily by using two lenses of particular powers in a plus-minus combination in which the axial separation of the lenses could be varied. A lens system conforming to the above requirements has lens components the separation of which is variable and adjustable, and the components of which are so dimensioned and arranged, that upon changing the separation, the virtual image of an object seen through the system remains substantially at the position of the object, but does change its size according to the prevailing separation.

The unit is most satisfactory when designed for use at reading distance; that is, a distance of about 40 cm from the eyes. At this distance one can make use of a simple concept of geometrical optics and select the power of the objective lens so that the longitudinal or axial magnification is unity. The principle, which hardly needs repeating here, is shown in Fig. 1.

For a small axial displacement of the object, the image is correspondingly displaced in the same direction and changed in size. Obviously, if the position of the object remains fixed, and the lens is slightly displaced along the axis

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* Presented at the twenty-sixth annual meeting of the Optical Society of America, held in New York City, October 24–25, 1941.

[1] K. N. Ogle, "The correction of aniseikonia by means of ophthalmic lenses," J. Opt. Soc. Am. **26**, 323 (1936).

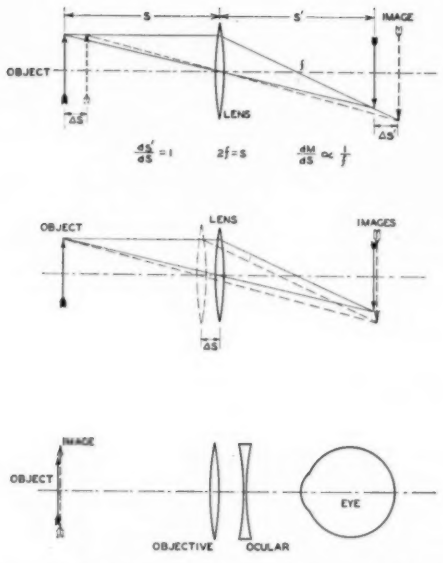

FIG. 1. The relationship between the various optical dimensions of a lens for an axial magnification of unity, and the principle of the variable magnification unit for a near object.

under the same conditions, the position of the image of the object remains substantially fixed, though magnified. This magnification is approximately proportional to the power of the lens and the magnitude of the displacement.

By combining a negative lens with the positive objective lens, the position of the final image can be made to coincide with the object itself. Thus when the axial separation of the component lenses is varied by keeping the ocular lens in a fixed position, the unit is essentially without power error yet has a variable magnification approximately proportional to the separation. For the distance of 40 cm from the eyes, a change in separation from contact to 10 mm gives a change of magnification of 5 percent, with a power error at any separation not exceeding 0.01 diopter. This unit is ideal for use in the laboratory, for near vision work.

Obviously, a unit designed strictly on this principle, for use at greater visual distances, would not give a sufficiently wide range of magnification change. In order to obtain a 5 percent range, larger power errors must be admitted. The unit can be designed for the visual distance of 6 meters, however, which will have the 5 percent range in magnification and yet have a power error not exceeding 0.01 diopter for any given separation of the elements. Such an error would generally be permissible in ophthalmic practice.

It would appear that this system is that of an ordinary Galilean telescope. In one sense this is true. The changes of separation of the components in the Galilean telescope, however, where the powers of the elements are relatively large, are specifically for the purpose of changing the power of the system, whereas here a change in magnification with little or no change in power is desired.

In the actual design of the component lenses for the units, the magnifications introduced by the thicknesses and shapes of the lenses were taken into account. The particular units described here were designed so that when the component lenses were in contact, the unit actually would have a diminishing effect of approximately 1 percent. Thus there would be a separation at which the device would have unit magnification, that is, no actual magnifying effect.

This was accomplished by designing the surfaces of the lenses somewhat concave toward the object (Fig. 2). Flexing, or bending the lenses in this fashion would tend to increase the aberrations for oblique rays. However, as will be shown

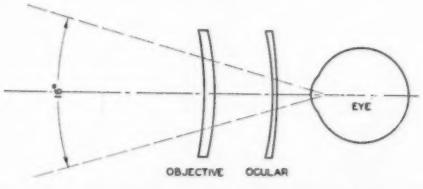

FIG. 2. The general plan of the unit for obtaining variable magnification, and a magnification less than unity when the component lenses are in contact.

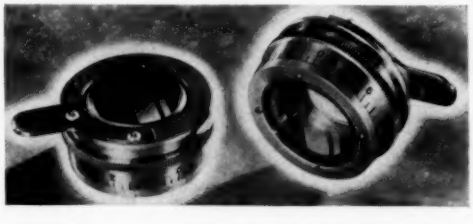

FIG. 3. A photograph of a unit for obtaining variable magnification.

later, these aberrations are small in the 16° field used.

Two types of units are generally required; one which gives an over-all magnification, and one which provides a magnifying effect in only one meridian, the meridian at right angles having unit magnification for all separations. The over-all unit has component lenses of the meniscus type with spherical surfaces. The meridional units, however, in order to provide the magnifying effect in one meridian only, will have component astigmatic lenses of the bitoric type, in

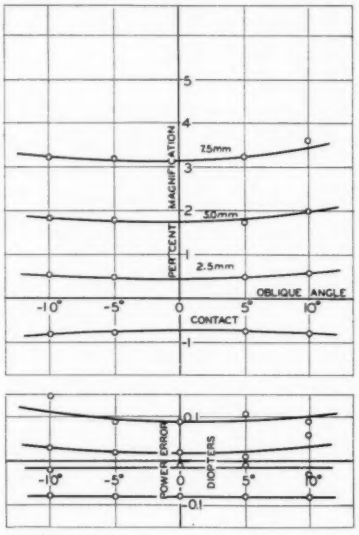

FIG. 4. Graphs illustrating the magnification and power properties of particular units used for distant vision.

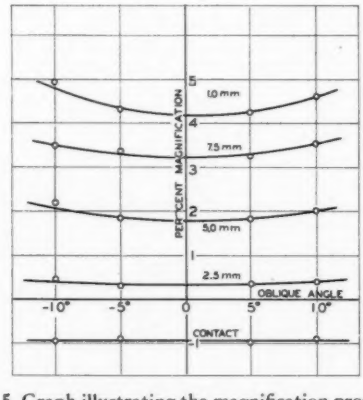

FIG. 5. Graph illustrating the magnification properties of particular units used for near vision. The power error was too small to be plotted.

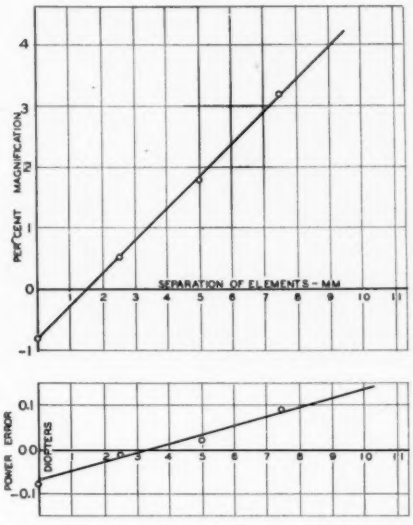

FIG. 6. Calibration curve for a particular variable magnification unit.

which both surfaces of each lens will be toric. For distance vision the surfaces of the component bitoric lenses will be plano in one meridian. For near vision, the curve of the meridian of no magnifying effect will have a radius approximately equal to the object distance. Considerable care must be taken in aligning the astigmatic component lenses in order to avoid, finally, the presence of astigmatism in the unit. Of necessity, this requires excellent grinding technique. The lenses of the first meridional units made, were cemented doublets with the cemented surfaces equally spheric, each element being a single toric lens. At present the bitoric lenses are being ground from a single piece of glass.

The component lenses are mounted in an aluminum cylinder; the ocular lens being fixed at one end, while the objective lens is propelled in a sleeve along the cylinder by pins in a helical groove activated by a ring on the outside of the unit. A scale that is engraved to read percent magnification, is attached to this ring. See Fig. 3.

The units are measured for accuracy in power and calibrated for magnification on a special ophthalmic lens instrument.[2]

[2] A description of this instrument was presented at the fall meeting of the Optical Society held at Rochester, New York, October 1940, and will appear in print in the near future.

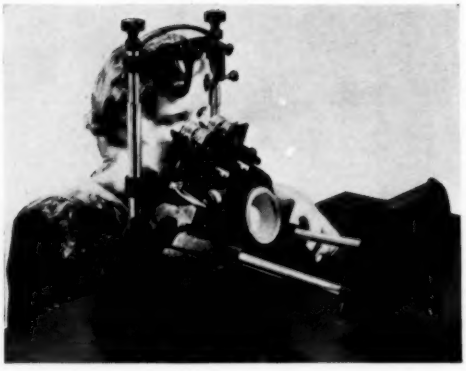

FIG. 7. Photograph illustrating a use of the variable magnifying units.

In Figs. 4 and 5 the optical properties of the two units are shown for several separations of the component lenses. These particular units are used at a distance of about 25 mm from the eyes. The abscissa in each graph represents the angle of an oblique ray through the unit measured from the axis of the unit at the eye; in the upper figure the ordinate represents the percent angular magnification and in the lower figure the power error in diopters. As indicated above, the flexing of the component lenses for the particular units described here does introduce pincushion distortion. This distortion, which appears somewhat large, is due primarily to the power error in the oblique directions and to the relatively increased distance of the units from the eye. However, in the particular instrument where these units are used, the field is less than 10°, and the power and magnification errors are both negligible. Reducing the flexure of the component lenses makes the pincushion generally negligible even for larger fields. The power errors of these units are what would be expected from the theory. No astigmatism of oblique incidence was measurable within the 20° field.

A typical calibration curve is illustrated in Fig. 6, where the abscissa represents the separation of the component lenses, and the ordinate represents the percent angular magnification. When the lenses are in contact, these units have a negative percent magnification; they actually decrease the size of the image.

Figure 7 shows how these particular lens units are used in an instrument. In this photograph four units are in use, an over-all and a meridional unit before each eye.

On the Nature of a Polished Surface*

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(Received November 25, 1941)

RAYLEIGH[1] was one of the first to show by means of the microscope that polishing a surface is a process different from that of even the finest grinding; he concluded from his microscopic studies that polishing is a molecular phenomenon caused by the adhesive forces between the molecules of the polishing agent and those of the surface. Beilby[2] added further to this idea by demonstrating that the polished layer resembles a film of viscous liquid and appears amorphous (in the case of polished crystalline solids) to the highest powers of the microscope. An examination of a polished surface with a microscope shows that the pits and scratches of the previous grinding are not eliminated by a wearing down of the surrounding surface but rather that these scratches are filled in by a flow of the surrounding material.

Where one is dealing with a crystalline solid, the study of the polishing process is made easy by the fact that the polishing destroys the crystalline nature of the surface and builds up an amorphous layer. One can investigate the thickness of this layer for crystalline substances by dissolving the layer in a suitable acid until the underlying crystalline structure is reached. Thus in the case of calcite N. K. Adams[3] reports that the completely amorphous layer was roughly 50A thick and that the flow lines produced by the fibers of the moving wash-leather were found at depths of 250–500A and some traces of the original ground surface down to 5000–10,000A.

POLISHED GLASS SURFACES

In the case of amorphous substances such as glass the investigation of the depth of the polished surface is difficult since there is no underlying crystalline structure upon which the polished surface rests. That the polished surface is, however, different in structure from the underlying glass can be easily demonstrated by subjecting the polished surface to the action of dilute hydrofluoric acid.

If the polished surface is placed in dilute hydrofluoric acid for a short time, the high polish is not in general destroyed, but the surface becomes covered with innumerable scratches and pits of varying length and depth. Although many of these scratches exhibit a curvature which might be ascribed to the circular motion of the fine grinding machine, the evidence that these scratches are those originally produced in the glass by the fine or rough grinding before the polishing began is not conclusive. Another explanation which might be offered to account for these scratches is that as the polished surface is etched off by the acid, the rearrangement of the molecules in the newly formed surface gives rise to stresses which cause the surface to crack.

Although we may not conclude that all the scratches which appeared after the acid treatment were present before the surface was polished, the following simple experiment demonstrates that scratches which are present on the surface before the surface is polished will reappear after polishing if the surface is treated with hydrofluoric acid.

On a highly polished glass surface (hard crown glass) several faint scratches of definite shape (letters and geometrical patterns) were traced by means of a steel razor edge. The surface was then placed on the polishing machine and rouge-polished until no trace of the original scratches could be discerned even under a microscope. The surface was then placed for a few minutes in a very dilute solution of hydrofluoric acid and carefully examined. All the marks scratched on the surface by the razor edge reappeared in a more pronounced form than they originally had.

It is clear from this result that the process of polishing is a molecular one; the forces of adhesion between the molecules of the polishing agent and those of the glass cause the glass surface to flow and fill up the cracks, pits, and

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.
[1] Lord Rayleigh, Nature **64**, 385 (1901).
[2] Beilby, *Aggregation and Flow in Solids* (1921).
[3] N. K. Adams, *The Physics and Chemistry of Surfaces* (The Oxford Press, 1938), p. 170.

scratches. This filling up process, however, does not obliterate the scratches in the sense that no distinction exists between the polished layer and the underlying surface. The action of the acid seems to indicate that the glass which has flowed into any surface deformities as a result of the polishing is more loosely bound to the surface than the surrounding glass and is therefore more easily removed by the acid.

These results are of some importance in considering the degeneration which polished surfaces may suffer if not sufficiently protected over long periods of time. However highly polished and free of defects a surface may appear, it will, if not well protected from acid influence, develop scratches after a sufficiently long period of time.

THE REACTION OF HIGHLY POLISHED SURFACES TO ACIDS OTHER THAN HYDROFLUORIC

A good deal of attention has lately been given to the preparation of surface films on glass in order to improve the light transmission through such surfaces; the most recent work in that direction was reported by Frank L. Jones and Howard J. Homer,[4] who have successfully prepared such films by treating glass surfaces with dilute acids. In view of the effects discussed in the previous section, it was considered important to determine whether such acid treatment would produce any scratching. To this purpose a dense barium glass (highly polished prism surfaces) was subjected to cold dilute nitric acid (10–20 percent solution) treatment for lengths of time varying from 5 to 100 hours.

The effects obtained as far as the reflecting films are concerned were similar to those described by Jones and Homer in reference 4. Prisms treated for about 10 or 12 hours showed violet and blue surfaces in reflected light: and the colors of these films on surfaces treated for longer periods showed a gradual transition from blue to red depending on the length of treatment. Prisms kept in acid for as long as 60 hours looked red in reflected light.

In order better to study the dependence of the color on the time of treatment, a number of prisms were placed in a shallow layer of acid base down so that the acid extended half way up the other two sides. These prisms were left in the acid for about 60 hours during which time the acid solution had evaporated to about 4/5 of its original amount. The effects of the different time exposures could be studied by observing the colors on two sides that had been only partially immersed in acid. Because of the evaporation of the acid, the time of exposure to the acid was shorter for points high up on the side than for those near the base. An examination of the two sides in reflected light showed a continuous transition of color from deep violet (the highest point reached by the acid and therefore the part treated for the shortest time) to deep red near the base.

These acid treated surfaces were carefully inspected for scratches, but in no case were any scratches found which had not already been present before the acid treatment. The longest period of acid treatment lasted for about 100 hours; here second-order interference effects could be observed since the reflected color depended on the angle of observation. But still no scratches were found.

This work was carried on at The Optical and Film Supply Company, and I wish to thank Mr. Mark Girard and Mr. Frank Siegel of that company for technical aid.

[4] Frank L. Jones and Howard J. Homer, J. Opt. Soc. Am. **31**, 34 (1941).

Time Effects and Arc Intensities*

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A PREVIOUS report[1] has discussed the effects of some physical characteristics of an arc on line intensities, with their implications for some problems of quantitative spectrochemical analysis. A further study of these effects will be presented at this time. In these studies, interest has centered on the factors limiting the useful concentration range of spectrochemical analyses, and on the shape of calibration curves of intensity as a function of concentration.

As a basis for comparison with observed intensities, we shall use as before the intensity of emission from a small volume of gas in the arc column free from disturbing factors, or, in other words, the intensity of emission from an optically thin layer of gas in thermodynamical equilibrium at temperature T. This quantity, which we shall call F_{nm}, for a line representing a transition from an upper level m to a lower level n of the atom, may be determined theoretically according to

$$\log F_{nm} = \log g_n f_{nm} \nu^3 - 5040 E_m/T,$$

where g_n is the statistical weight of the nth level, f_{nm} is the Ladenburg f, or oscillator strength, ν is the frequency of the line emitted, and E_m is the excitation potential of the mth level of the atom in electron volts.

Empirical determinations of f, and hence of F, may be most conveniently made by measuring the intensity of lines from an absorption furnace. In order to make available data for a larger number of elements than have been studied in absorption, the author has made use also of values of F approximated from intensities of emission in an arc. By using low arc currents and low concentrations of the element being studied, one can attain the necessary condition of a thin emitting layer, and thus determine F directly. At the same time, if the arc contains in addition an element whose f-values are known from absorption line intensity measurements, one can use the observed emission intensities of the latter element to determine the temperature, and thence the f-values for the unknown element.

This procedure has been used to study intensities in NiFe and in NiCo alloys. Within the observational error, which is about $\pm 100°$K, the temperature at the center of the positive column has been found to be 4200°K under fixed conditions of operation of the arc (14 mm arc gap, 1.5 amperes arc current). The temperature is insensitive to changes of composition of the electrodes, for the several observed systems of alloys.

The observational procedure used has been substantially similar to the one previously described. All observations were made with a thirty-five foot stigmatic grating spectrograph, and a wide (0.1 mm) slit. Each plate was calibrated with a step-sector exposure of a line source, and standardized by exposure to a tungsten ribbon-filament lamp operated at a known temperature. Densities were measured with a non-recording microphotometer sensitive to optical densities up to 3.0.

The optical system between source and slit deserves description in further detail. It was desired to isolate light from a particular portion of the arc, to obtain greater homogeneity of physical conditions in the part of the source observed. Two lenses of equal focal length were therefore used; the first focused the source at a point outside the slit; the second lens, placed at the image of the source, focused the first lens on the slit. At the second lens was an aperture excluding all light except that from the positive column of the arc, away from the cathode flare. Distances were so chosen that the spectrograph aperture was just filled vertically; since the horizontal aperture is larger than the vertical, the intensity at the focus of the spectrograph was thus substantially independent of the inevitable slight flickering of the arc from side to side. In addition to satisfying the main purpose, of photographing only such a portion of the arc as can most satisfactorily be interpreted in terms of a temperature parameter, this system has the

* Presented at the Ninth Summer Conference on Spectroscopy and Its Applications at Massachusetts Institute of Technology, July 21–23, 1941.

† Bausch and Lomb Research Fellow.

[1] H. Hemmendinger, J. Opt. Soc. Am. **31**, 150 (1941).

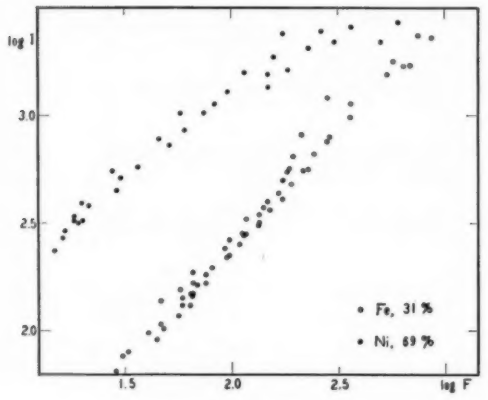

FIG. 1.

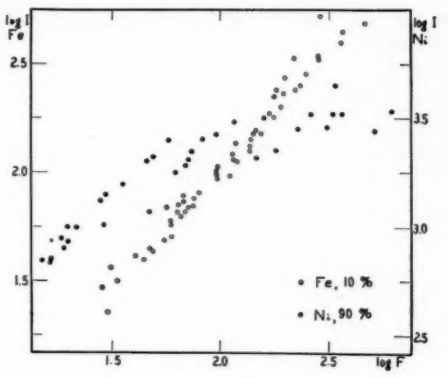

FIG. 2.

advantage of excluding any continuum either from the cathode flare or from the electrode tips.

Figures 1 and 2 will serve to demonstrate the behavior of intensities in an arc, the effects of self-reversal, and the method of determining relative intensities of two components of an alloy independent of self-reversal. In these graphs, the abscissa is log F, and the ordinate is the logarithm of the intensity of the lines of each element. The first graph (Fig. 1) shows the results for an alloy of 69Ni+31Fe. The diminution, by self-reversal, of the intensity of the stronger lines may be observed, particularly for Ni. The intersection of the linear portion of each curve with the abscissa log $F=0$, which we shall call I_0, may be taken as a measure of the intensity of the corresponding element in the arc. A valid criterion of the concentration ratio of two elements in the arc is evidently the ratio of these two intensities, or its logarithm: $\log I_0(\text{Ni}) - \log I_0(\text{Fe})$. Figure 2 shows a series of similar measurements of an alloy composed of 90 Ni +10 Fe; the greater self-reversal of Ni is evident, yet by confining one's measures to the lower portion of the curve, one may eliminate the effects of self-reversal on the intensity ratio of lines of the two elements. In practice, it is not necessary to measure each time a large number of lines of each element, but merely a few of sufficiently differing log F so that one may determine at what value of the intensity the lines may be deemed free of self-reversal. It has appeared, in fact, that a sufficient, though not a necessary condition for the elimination of effects of self-reversal is that the lines measured shall be not more than one-tenth as strong as the strongest lines to the ground state of the atom. With a photographic plate of contrast approximately one, it is therefore sufficient to expose for such a length of time that the strongest lines to the ground state are "burned out" on the plate, that is, have a density of 3.0 or more. If one then confines his photometry to lines of density less than 2.0, as is usually most convenient anyway, he may be sure that none of the observed lines is appreciably reversed.

A large number of measures such as those of the preceding graphs have been made, and have

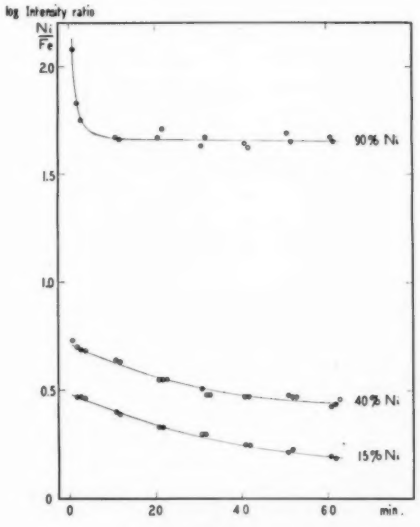

FIG. 3.

proved adequate to determine intensity ratios of two elements in an arc at a given time with a probable error of ±2 percent. However, successive observations with a given alloy have not proved reproducible with the same accuracy, and the cause of the variations has therefore been investigated. It has been found to lie at least partially in the variation of composition at the tip of the electrodes as the arc continues to burn.

Figure 3 shows a series of typical results of these variations with time. The ordinate is the ratio of intensity of Ni to that of Fe; the abscissa is time after ignition of the arc in minutes. It will be observed that in the case of an alloy of 90 Ni+10 Fe the rate of change of intensity is at first rapid, and the ratio becomes constant after a few minutes. On the other hand, in the case of alloys containing a greater proportion of Fe, the rate of change is gradual, and the intensity ratio approaches a constant value only after an hour or more.

So far these results are familiar to users of spectrochemical techniques. It has usually been found adequate to wait at most a few minutes after ignition of the arc before a substantially steady state is reached. However, the present

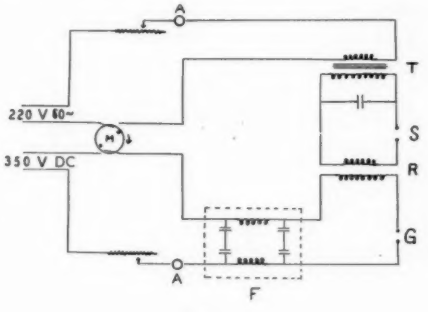

FIG. 4.

results suggest that that is not necessarily to be anticipated when one is dealing with electrodes not consisting primarily of a single element.

Let us consider what means may be employed to minimize these variations with time. They evidently arise in the gradual changes taking place at the electrode tips, due to differential evaporation from the surface and differential diffusion from the underlying portions. The first of these factors, the differential evaporation, is

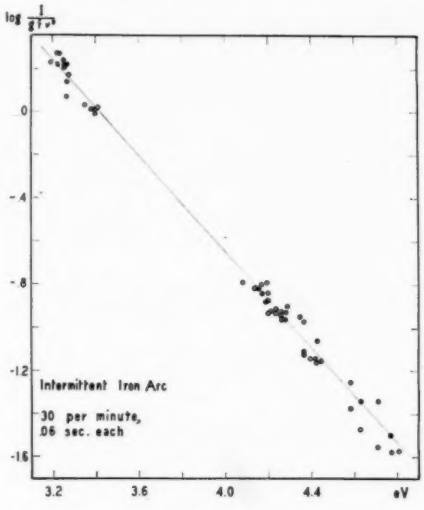

FIG. 5.

an essential feature of arc analyses. The second may be minimized by keeping the electrodes as cool as possible.

One means of doing so is to be found in an intermittent arc, such as has been described by Pfeilsticker.[2] He has used as a means for igniting the arc a superposed discharge of a high frequency spark. A slight modification of his circuit has been constructed here; a schematic diagram is shown in Fig. 4.

The source consists essentially in two parallel circuits, discharging through a common arc gap *G*. First, there is an a.c. input and 5000-v transformer, discharging across a condenser and auxiliary spark gap *S*. A resonance coil, or air-core transformer, *R*, provides a high frequency discharge which jumps across the main gap *G*, passing through the first pair of condensers in *F*. The ionization produced by this spark at *G* is sufficient to allow a d.c. arc to strike, the current for which has entered through the second parallel circuit and is passed by the inductances in *F*. The high frequency discharge is prevented by the latter inductances from entering the d.c. supply mains.

In use, both circuits are opened and closed by contacts on a rotating wheel *M*. The contacts are adjusted so that the d.c. circuit is closed

[2] K. Pfeilsticker, Zeits. f. Elektrochemie, **43**, 719 (1937).

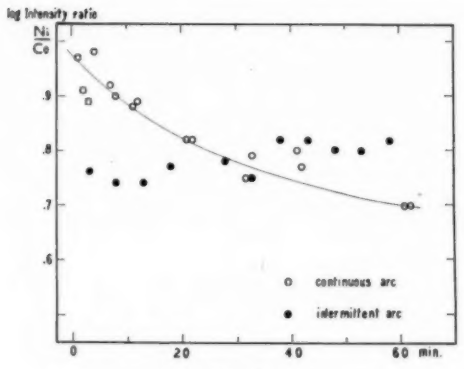

FIG. 6.

first, and at a later instant the a.c. circuit is closed. The latter, striking a spark at G, remains on merely long enough to make the arc strike; then the a.c. circuit is opened, and at the same time, or later, the d.c. circuit is opened. Thus a means is available of keeping the arc on for any desired fraction of a cycle; the frequency of discharges may also be varied by a change in the motor speed at M. Typical values used by the author have been: frequency 15 to 60 cycles per minute, spark on 0.03 cycle, arc on 0.01 to 0.15 cycle. Because the circuit has not been investigated for optimum values of the various inductances and capacitances, the values used are not given here.

The nature of the discharge closely resembles that of a continuously burning arc. The spark itself contributes a negligible amount of energy to the discharge; the spark lines are not visible on an exposure of such length that the arc lines may be conveniently measured. The temperature of the center of the positive column has been determined by the method described in the previous paper. Figure 5 shows a graph of the observational data for an intermittent arc between pure Fe electrodes with an electrode separation of 8 mm and a low arc current. (The external resistances in the arc circuit were such that the current through a continuously burning arc would have been 1.50 amperes. The instantaneous current of the intermittent arc was not measured.) The ordinate is proportional to the apparent number of atoms in a given atomic level from which a line arises; the abscissa is the excitation potential of that level in electron volts. The apparent populations conform as well with a Boltzmann distribution as do those in a continuously burning arc. The temperature represented by this figure coincides within the error of observation with that of a continuously burning arc with the same electrode separation. The electrode tips do not become too warm to touch with comfort; the only signs of melting are at small points on the surface of the electrodes, where the arc has caused a myriad of small molten spots to appear. Even in the case of lead electrodes the whole tip does not become molten when the intermittent arc is used.

Some results of the use of this source are indicated in Fig. 6. The open circles show the ratio of intensity of Ni to Co in an 80 percent Ni alloy as a function of time after ignition of a continuously burning arc. The change is considerable, the ratio approaching a constant value after about an hour. With the intermittent arc, as shown by the full circles, there is no continuous change with time. There is an appreciable scatter, greater than the error of observation, whose source is yet to be identified.

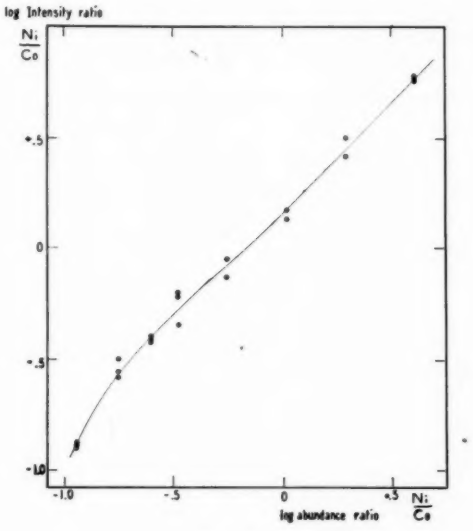

FIG. 7.

A further result of the use of this source is shown by Fig. 7, in which, for a series of alloys of Ni and Co ranging from 15 to 90 percent Ni, the intensity ratio in an intermittent arc is

shown as a function of the weight ratio of the components of the electrodes. Each point is a mean value for four observations. The scatter is still somewhat greater than is desired; it represents a possibility of analysis with a probable error for a single determination of about ±8 percent of the amount present.

One particular feature of this last curve is of interest for reasons in addition to possible uses in analysis: the deviations from linearity. These deviations, on the lower end of the curve, are greater than observational errors. If the material in an arc leaves the electrodes by methods primarily thermal in character, the deviations may perhaps be ascribed to departures of the liquid-gas system of Ni—Co alloys from Raoult's law. Such departures, which are more common than regularities in the case of observed liquid-gas systems, have as yet been studied for molten metals only in the case of low melting alloys. The comparison of spectroscopic results with such observations suggests a possibility of investigating the mechanism whereby atoms are supplied to the arc column from the electrodes.

Further investigations of the properties of certain sources related to the intermittent arc described, and of the mechanism of formation of arcs in general, are in progress.

MARCH, 1942 J. O. S. A. VOLUME 32

Voltage Regulator for a Densitometer Lamp

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(Received December 6, 1941)

THE use of the spectrograph as a means of rapid control analysis as well as a versatile laboratory instrument is well known. Most of the procedures developed for quantitative spectrochemical analysis make use of a microdensitometer for measuring the densities of the spectral lines, and the trend is towards an instrument which can be used at high speed with a minimum of strain on the operator. These requirements have brought the projection type of microdensitometer into almost universal use. It has been pointed out[1] that the light source should be free from variations in intensity to at least 1/10 of 1 percent. Using the simplified Bureau of Standards equations[2] this means that the voltage applied to the lamp terminals must be held constant to about 0.03 percent, a requirement which the average laboratory supply main is far from fulfilling, especially if the installation is in a steel mill or an iron foundry.

There are magnetic regulators commercially available that will greatly improve the line voltage; however, they do not provide regulation of the above magnitude, and they are also sensitive to deviations in the supply frequency. Another solution is the use of batteries as the lamp supply. This necessitates some sort of "trickle" charging arrangement or a switching system for spare batteries which involves considerable maintenance for high precision analyses. The use of batteries usually limits one to the use of a low voltage type projection lamp, thus making the stability requirements more difficult to fulfill.

The purpose of this paper is to describe the application of the regulator circuit used in

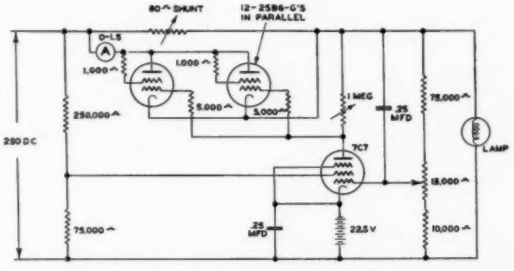

FIG. 1.

[1] R. A. Sawyer and H. B. Vincent, J. Opt. Soc. Am. **31**, 51 (1940).
[2] P. Moon, *Illuminating Engineering*, p. 162.

precision radio receivers[3] to the control of the lamp voltage of a microdensitiometer. Circuits of this type have been known for several years and one article[4] has been published describing such a regulator which controls the lamp used in a device to integrate the product of two mathematical functions by means of light beams. A modification of the circuit has been built in the Engineering Research Laboratory of the Hygrade Sylvania Corporation and has been in use now for a year (see Fig. 1). The apparatus makes use of small electronic tubes of the type used in radio receivers and requires very few other parts. Therefore, being quite inexpensive and yet reliable, it was thought that a description of this device might be of interest to other workers in the field of quantitative spectrochemical analysis.

The projection lamp used in our microdensitometer is a 250-watt, 115-volt, monoplane filament type which draws about 2 amperes under normal operation conditions. Currents of this magnitude are beyond the capabilities of conventional regulator circuits using radio tubes. By using 12 type 25B6G tubes in parallel and the shunt circuit described by Bousquet,[5] the necessary rating was achieved. Essentially, the circuit operates as follows: Let us suppose the lamp voltage drops a small amount. This causes a slight change in the grid voltage of the 7C7 control tube with respect to the constant e.m.f. of a battery. This change is amplified and applied to the grids of the 25B6G regulator tubes in the correct phase so that the tubes pass more current and tend to restore the lamp voltage to its original value. The inverse occurs if the lamp voltage rises a small amount. The reference voltage is supplied by a 22½-volt battery, the life of which is long as it is called upon to deliver only about 2 milliamperes current. In our installation, regulator life and shelf life of the battery are of the same order of magnitude. We replaced the battery at the end of ten months' operation; however, it later appeared that this was not necessary. The degree of regulation of the system is dependent upon the gain of the control tube circuit. In our case, we have found that adequate

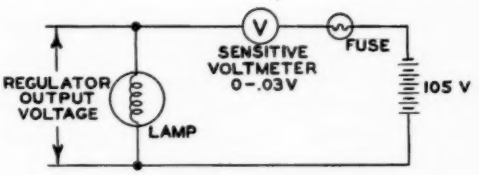

FIG. 2.

gain is achieved in our regulator by bringing the screen of the 7C7 out to a voltage divider at the input end of the circuit where it acts on an input voltage change in the same manner as the control grid. This greatly simplifies the apparatus. The regulator tubes are 25B6G's connected as triodes and 12 of them in parallel are used to handle the current. In normal operation, about 0.75 ampere flows through the tubes while 1.5 amperes are carried by the shunt resistor. This type of regulator tube was chosen because the filaments of five of them can be put in series and run directly off the 115-volt line, thus eliminating all transformers. The screen grid should be tied to the plate through a resistor to prevent excessive screen dissipation.

The d.c.-input voltage to the regulator is obtained from the same generator that supplies the current to the d.c. arc used in qualitative spectrographic analysis. This source of power is convenient rather than necessary. A well-filtered conventional rectifier system would work just as well. Since the arc is frequently operated while densitometer measurements are being made, the regulator has to compensate for line voltage swings as high as thirty volts (12 percent). It will reduce a line voltage change of 23 volts in 245 to a change of 0.0035 volt in 106 at the lamp terminals. The latter is a change of 0.0033 percent. This regulator then is satisfactory since it holds the line voltage constant to better than 1/30 of 1 percent for sudden changes in line voltage. The 55-volt drop from 245 to 190 volts caused by the initiation of a 15-ampere arc produces but a momentary 1-mm change when the galvanometer deflection is 500 mm.

We have also made some measurements on voltage drift over a period of time. The drift requirements for our installation are not severe since we are using our instrument as a spotting microdensitometer and all readings are finished

[3] G. Grammer, Q. S. T. **21**, 14 (1937).
[4] J. N. Coombs and P. T. Nims, Electronics, **13**, 40, 44 (1940).
[5] A. C. Bousquet, Electronics **11**, 26–27 (1938).

within from 10 minutes to a half hour. The potentiometer in the grid circuit of the 7C7 control tube is mounted directly on the instrument control panel and is used for a manual light control, the reading through the clear emulsion of the photographic plate being set to zero on the scale when the plate is placed in the instrument. We then require that the lamp voltage not drift during the time needed to make all readings on the plate. To check this, the densitometer lamp was run continuously for a period of six hours at its normal operating voltage of 105 volts. This voltage was compared with the e.m.f. furnished by a battery connected in the circuit shown in Fig. 2. Since the d.c.-lamp potential and the battery potential were made very nearly equal, less than a milliampere flowed through the battery so that its potential remained constant. During the 6-hour time, the lamp voltage drifted 0.030 volt, a change of 0.029 percent. Thus, the drift was found to be less than the limit set for random variations in lamp voltage. Average line fluctuations do not effect the drift of the microdensitometer; however, if the line voltage changes and remains at the new value there is a slight drift introduced due to the change in cathode temperature of the 7C7 control tube. If this drift becomes objectionable we plan to operate the filament from the regulated output voltage. In our present work this has not been necessary.

In order to obtain satisfactory regulation it is necessary to adjust the circuit carefully; however, once set it remains in adjustment until a new densitiometer lamp has to be installed. In our case, we obtain proper setting by introducing voltage surges in the d.c. line by making use of the arc equipment previously mentioned. The electrodes are brought together and enough resistance inserted in the circuit so that about 12 amperes flow. The switch to the arc is then turned on and off while the effect is noted on the full scale deflection of the densitometer galvanometer. By adjusting the 1-megohm resistance in the plate circuit of the 7C7 control tube, it is possible to make the regulator overcompensate or under-compensate for the sudden input voltage changes. By proper adjustment of this control the system can be brought to a point where the input surge does not shift the densitometer scale deflection from its equilibrium position. Of course, there are other ways by which one could cause the input voltage to vary; for example a resistor in series with one of the input conductors arranged so that it could be periodically shorted out would be fully satisfactory. For a very careful adjustment we have used the circuit shown in Fig. 2 to indicate the best regulation. As a test of stability, a set of 50 repeated measurements was made on a pair of lines photographed on an Eastman type 33 plate. These showed that the densitometer variations introduced a standard deviation $[\Sigma D^2/(n-1)]^{\frac{1}{2}}$ in the determination of 0.000025 percent copper of one percent.

It is felt that this article will be of interest to those working in applied spectroscopy not because the application is unique but in the hope that those who are unable to keep in touch with electronic developments will find it useful. For this reason the circuit constants are all given as are directions for putting the system into good adjustment. I wish to acknowledge my indebtedness to Mr. F. L. Burroughs of our Tube Application Department who designed the circuit and who suggested the idea of bringing the screen of the 7C7 control tube out to a voltage divider across the input, a suggestion which increases the precision of the regulator as well as simplifying the circuit.

The Fluorescence of Phosphors in the Rare Gases

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Research Laboratory, General Electric Company, Schenectady, New York

(Received November 26, 1941)

The spectral distribution for the excitation of phosphors is so erratic that it seems at present impossible to predict the location of strong excitation bands. Out of many phosphors examined in rare gas discharges, none was found to exceed in brightness the calcium tungstate and zinc silicate already in commercial use. The light output of the latter, however, was considerably improved by the elimination of the free silica usually present, which evidently has an appreciable absorption to radiation in the Schumann region. On the reasonable assumption that the resonance radiation is the source of excitation, the efficiency of fluorescence emitted by the zinc orthosilicate phosphor in the neon discharge denotes a quantum conversion near unity, just as in the low pressure mercury discharge.

THE present fluorescent lamps take advantage of the high efficiency of excitation characterizing certain phosphors when subjected to the resonance radiation of a low pressure mercury discharge.[1] These phosphors include silicates and tungstates. Certain other phosphors, well known for their brightness, such as the sulfides, cannot be used in this lamp because their efficiency of excitation, though high in other parts of the spectrum, is low under the 2536A radiation of mercury.

Other combinations of a phosphor and a gaseous discharge are presumably possible. The primary essential is that the radiation of the discharge shall be strong in a spectral region capable of exciting the phosphor efficiently. The most available gaseous discharges, in addition to those in mercury vapor, are those in the rare gases. Their radiation in the ultraviolet, however, is most prominent in the resonance lines which lie at the very short wave-lengths characterizing the Schumann region. If radiation of such short wavelength is to act as the exciting source of fluorescence, the energy yield of luminescence emitted by the phosphor will be much more limited than under excitation by the 2537A line of mercury because of the much more unfavorable quantum ratio, i.e., the ratio of the integrated energy per quantum of fluorescence radiation to the energy per quantum of the exciting line. Despite this handicap, however, Jenkins found it possible to obtain new and useful color effects or an increase in lamp efficiency or both by coating neon or helium discharge lamps internally with zinc silicate or calcium tungstate phosphors.[2]

Jenkins and Bowtell have already presented the results of their investigations for the case of zinc orthosilicate in neon discharge tubes.[3] Their aim was to determine the values of current density, gas pressure and tube diameter that would represent the best operating conditions for obtaining optimum luminous output, efficiency, life, and color.

It was the aim of the present work to investigate the possibility of further gains by studying the luminosity of other phosphors as well as of zinc silicate and calcium tungstate under excitation by discharges in the other rare gases as well as in neon and by attempting an evaluation of the quantum yield.

The tests were made by coating the phosphor on a glass disk 1.5 cm in diameter which was then mounted in a 2.6-cm diameter tube with a hot cathode. Gas at various pressures was admitted to the tube on the pump and a direct current discharge was operated in it. The intensities of the luminescence emitted by the various coated disks present in the tube were measured by focusing each in turn upon a photo-voltaic cell with a filter to correct its sensitivity to that of the eye. The luminescence as measured included not only (a) the fluorescence of the phosphor but also (b) the luminescence of the gaseous discharge as reflected from the surface of the phosphor. The

[1] G. E. Inman, Trans. I. E. S. **34**, 65 (1939).

[2] H. G. Jenkins British Patent 457,486 (1935); A. Ruttenauer, Zeits. f. tech. Physik **17**, 384 (1936); J. T. Randall, Roy. Soc. Arts **85**, 354 (1937).

[3] H. G. Jenkins and J. N. Bowtell, Trans. Faraday Soc. **35**, 154 (1939).

magnitude of (b) was determined directly by measuring the brightness of a disk coated with aluminum oxide as a non-fluorescent material. As the disks were all of uniform size, the value of (b) subtracted from the total brightness emitted by a phosphor yielded the value of (a), the fluorescence alone. The absorption of fluorescence by the luminescence of the gaseous discharge was apparently negligible.

It was established in the experiments of Rüttenauer[2] and by Jenkins and Bowtell[3] that excitation of phosphors in the rare gas discharges is in fact to be ascribed to their resonance radiation, ranging from 584A in case of helium to 1469A in case of xenon. Out of the many compounds that we have examined, it developed that the extent of their excitation in the various rare gas discharges as well as by prominent lines in the mercury discharge, varied widely from one phosphor to another. Calcium oxide phosphors, for instance, showed in some cases a faint fluorescence under 2536A, a stronger one under 3650A, and a low fluorescence in neon. Magnesium silicate activated with manganese was unresponsive under 2536A or 3650A but in the rare gases developed fluorescence which was greatest in the heavy gases, argon, krypton, and xenon. Magnesium borate with manganese was excited only in argon and krypton. Fluorescent calcite was excited under 2536A and 3650A and in helium and xenon, but not in neon or argon. Zinc sulfide activated with copper, which is excited very strongly under 3650A and only weakly under 2536A, showed a very low fluorescence in neon, krypton, and xenon, but a stronger one in helium and argon.

Such observations made it apparent that the excitation of phosphors does not follow some obvious rule but varies in an erratic manner. It is at present impossible to predict in what spectral region a phosphor will respond to excitation. The presence or absence of an excitation band at some particular range of wave-length has therefore no present significance in denoting the extent or location of an excitation band in another region of the spectrum.

So far as excitation in the rare gases is concerned, it was found that zinc silicate and calcium tungstate, out of many compounds examined, did in fact develop the highest brightness and that this brightness was greater in neon and in helium than in the other rare gases, just as claimed by Jenkins.[2] The fluorescence from cadmium silicate and borate, activated with manganese, and from magnesium tungstate was likewise high, in accord with recent observations by Suga and Kamiyama.[4]

The fluorescence of all varied similarly with changes in gas pressure and current and developed peaks or stable values whose location and magnitude showed characteristic differences depending upon whether the gas involved was in the lighter or heavier group. The fluorescence increased continuously with pressure in neon and helium, for instance, as brought out by the curves of Fig. 1 for the typical case of zinc silicate, and approached a uniform value when the pressure reached the range of 500–1000 microns. It attained a maximum at a somewhat higher pressure and thereafter decreased. This was in marked contrast to the fluorescence observed in the heavier gases, argon, krypton, and xenon, the results for the last being very close to those shown in the curves for krypton. In these heavier gases there was a pronounced peak in intensity at

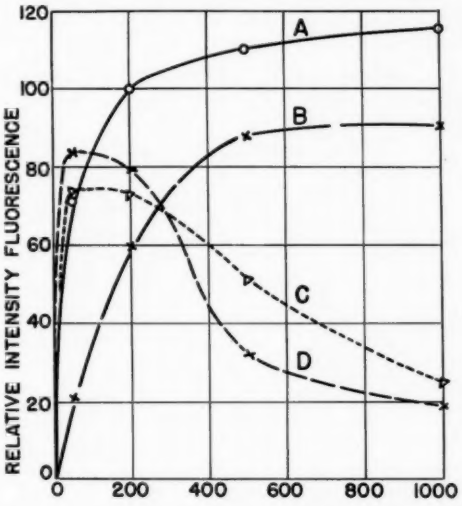

FIG. 1. The relation between the fluorescence of zinc silicate phosphors and gas pressure in rare gas discharges at an arc current of 200 mA. *A*—neon; *B*—helium; *C*—argon; *D*—krypton.

[4] Taro Suga and Masahide Kamiyama, J. Opt. Soc. Am. **31**, 592 (1941).

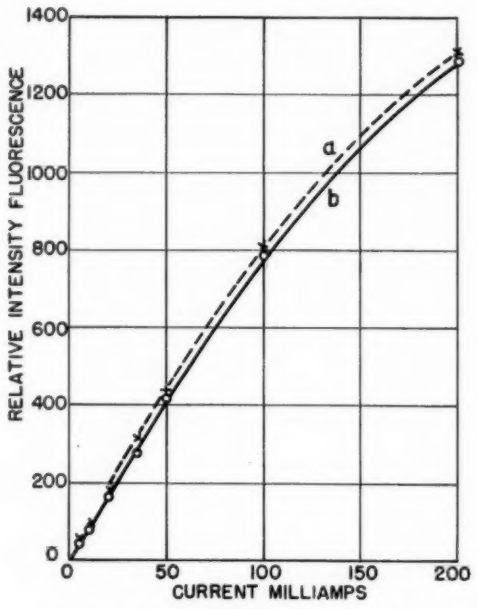

FIG. 2. The fluorescence of zinc silicate phosphors in the low pressure mercury vapor discharge. a—$Zn_2SiO_4 \cdot Mn$; b—$Zn_2SiO_4 \cdot SiO_2 \cdot Mn$.

low pressures, 50–200 microns, where clean-up and sputtering became serious under continued operation.

Such an occurrence of a maximum value for the excitation of phosphors on increase in gas pressure is related to similar changes in the intensity of resonance radiation due to collision of the second kind which become more prevalent as the pressure rises. This in fact is one of the main reasons for assuming that it is the resonance radiation which excites their fluorescence. The occurrence of maximum fluorescence, however, at such a low pressure as 50 microns in argon, krypton, and xenon, as compared with the high optimum pressure observed in neon and helium, needs further explanation. One has been suggested by C. G. Found of this laboratory on the basis of the relationship between the efficiency of excitation of a gas and the magnitude of the electron temperature. Excitation begins at a critical electron voltage, rises abruptly to a peak at a somewhat higher voltage and then tails off gradually under the action of electron velocities having still higher voltage. The distribution of electron velocities, however, is displaced to lower values by an increase in pressure. It happens in the case of xenon, krypton, and argon, all three characterized by low excitation potentials, that the reduction in electron temperature with pressure is so marked that there is a serious decrease in the number of electrons of velocity greater than the excitation potential, a decrease which in fact predominates over the increase in number of gas atoms that accompanies the increase in pressure. The net result, therefore, is a reduction in the number of excited atoms formed and consequently in the intensity of the resonance radiation emitted in these gases. In the case of neon and helium, gases having higher excitation potentials, this situation would not arise until a higher pressure were reached. Actually the observed peak of fluorescence brightness in these latter gases occurred somewhat above 1-mm pressure. In neon the brightness at 2 mm was 50 percent of its value at 1 mm. In helium the corresponding decrease was only to 80 percent.

Similar differences between the lighter and heavier gases occurred for variations in current. The fluorescence of zinc silicate can again be taken as typical. It is of especial interest because the tests on it brought out also an effect of composition characteristic of the silicates and denoting a relation between loss of resonance radiation by absorption and the content of free silica in the phosphor. Although zinc silicate occurs only in one form, that of the orthosilicate, Zn_2SiO_4,[5] yet it is generally prepared with an excess of silica for use in the low pressure mercury vapor discharge type of fluorescent lamp. The excess silica facilitates completion of the reaction during preparation by assuring consumption of all of the zinc oxide present. The preparation of a satisfactory form of the orthosilicate alone is more involved. Fusion of the ingredients does, it is true, secure a ready reaction but the product obtained is low in fluorescence because of the necessity of grinding. When a mixture of the oxides is fired at a temperature below fusion, the reaction can be brought to completion only by grinding and refiring and the resulting product, although brighter than that obtained by fusion, is still not as bright as the normal phosphor. The completion of the reaction in one step is essential

[5] G. R. Fonda, J. Phys. Chem. **43**, 561 (1939).

to the attainment of full, normal brightness. It can be secured by starting with a colloidal solution of zinc and manganese nitrates in silica, thereby taking advantage of a characteristically more rapid rate of reaction.[5]

Such a phosphor was prepared and comparative measurements were made in the various gases on its fluorescence and that of the orthosilicate prepared similarly but with one mole of excess silica, $Zn_2SiO_4 \cdot SiO_2$. Both were activated with 0.5 percent manganese. As can be observed from Fig. 2, the fluorescence of both phosphors was essentially the same when tested in the low pressure mercury discharge. The two phosphors had likewise the same relative brightness when tested in the open air under a low pressure quartz mercury lamp. When tested in gaseous discharges, however, the phosphor with one mole of excess silica was invariably much less bright than the orthosilicate phosphor, as is brought out in Fig. 3.

It is to be inferred, therefore, that free silica has an appreciable absorption to radiation in the Schumann region as contrasted with a negligible absorption at 2536A.

A similar characteristic difference between the lighter and heavier gases is demonstrated in the curves of Fig. 3 by the occurrence of a much earlier saturation effect observable in argon and krypton with increase in current. The same is true of the results in xenon, which followed the same course as the curves shown for krypton. It occurs at a much lower current than was observed in neon and helium. It is due presumably to an earlier suppression of the resonance radiation. These curves bring out again the relatively strong order of fluorescence obtainable in neon and helium as contrasted with a lower order of fluorescence in argon, krypton, and xenon, denoting a peak in excitation in the range of 580–750A.

From two considerations it is probable that the efficiency of excitation of zinc orthosilicate by the resonance radiation in a neon discharge is close to the maximum that would be possible under a quantum conversion of unity. Under the most favorable conditions of current density and gas pressure, the intensity of fluorescence in neon was found to be 35 percent of that in low pressure mercury vapor at the same current. If fluorescence results in both cases from excitation by resonance radiation and if the same number of excited atoms are formed per electron in neon as in mercury, then one quantum of neon resonance radiation would produce 740/2536 or 29 percent of the fluorescence excited by one quantum of mercury resonance radiation, close to the 35 percent actually observed. The conclusion then would be that the quantum efficiency in neon is near unity, just as it is known to be under the 2536A line of the mercury discharge.

A high value for the quantum efficiency was also derived from consideration of the energy efficiency of light formation. The theoretical value for zinc silicate, the peak of whose fluorescence lies at 5300A, would be 520 LPW. Under

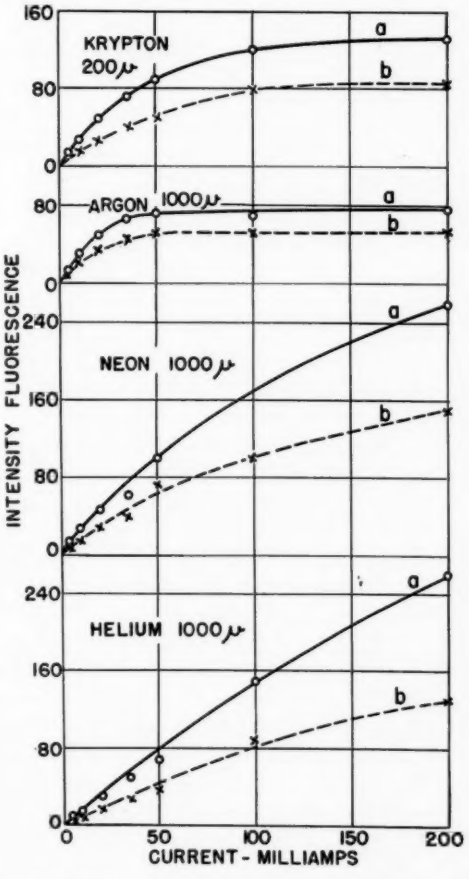

FIG. 3. The fluorescence of zinc silicate phosphors in rare gas discharges. a—$Zn_2SiO_4 \cdot Mn$; b—$Zn_2SiO_4 \cdot SiO_2 \cdot Mn$.

excitation by 740A, this would be reduced to $740/5300 \times 520 = 72$ LPW. The average efficiency reported by Randall[2] for a commercial type of neon lamp coated with zinc silicate, is 22 LPW as compared with 15 LPW for a neon discharge alone under the same conditions. This gives a value of 7 LPW for the efficiency of the fluorescent light alone, 10 percent of the theoretical on the basis of a quantum conversion of unity. When allowance is made for the reduction in resonance radiation at the relatively high pressure and current used commercially and also for its incomplete utilization in the necessarily thin film of phosphor, this value would become about 20 percent. The proportion which the energy emitted as resonance radiation bears to the total energy of the neon discharge is not known, but it is reasonable to suppose that it is not more than 30 percent. Here again therefore a high value for the quantum yield is apparent.

Both of these evaluations are necessarily approximate. They indicate, however, that the prospect is not favorable for the attainment of appreciably higher efficiencies by combination of a fluorescent phosphor with a neon discharge unless some radically new factor is introduced.

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Curve Shape Index for Identification by Means of Spectrophotometric Curves

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(Received October 25, 1941)

A simplified curve-shape indexing system for spectrophotometric absorption curves is described by means of which the tentative identification of an "unknown" (whose curve is already at hand) may ordinarily be made in 2 or 3 minutes even in the presence of small amounts of colored impurities. Quantitative solutions are not required.

INTRODUCTION

WHEN there are spectrophotometric absorption curves on file for 500 to 1000 dyes, rapid identification of unknowns requires that a simple curve shape index be available. If there were but a relatively small number of reference curves, it would, of course, be a simple matter to compare the curve of an unknown with all the reference curves. However, when the number of reference curves is large, such a procedure becomes too laborious.

Various systems of curve shape symbols have been proposed. Holmes *et al.*[1] discuss a number of these, including one of their own involving an "absorption ratio," the ratio of extinction coefficients at two arbitrary wave-lengths pre-selected for a given group of related dyes. However, it is not apparent how such a system could be extended to include all dyes in the same manner.

More recently, Godlove[2] has proposed a system of symbols in which, for a given curve, one first adjusts the data so that the minimum transmission value is exactly 10 percent, and then indicates the approximate transmission at each of *nine*, fixed, (more-or-less equally spaced) wave-lengths, starting at 400 millimicrons. However, this type of symbol presupposes either special experimental conditions for providing 10 percent minimum transmission or making graphical transformations to reduce the curves to equivalent form.

Further, a system employing prescribed wavelengths tends in practice to fail to give adequate emphasis to the most characteristic features of the absorption curve, and is, therefore, considerably disturbed by the presence of small amounts of colored impurities. Thus, for example, the very first number in the symbol for a blue, green, or black would by changed by

[1] W. C. Holmes, J. T. Scanlan and A. R. Peterson, "The visual spectrophotometry of dyes," Dept. Agriculture Tech. Bull. **310** (June, 1932).

[2] I. H. Godlove, paper in the Intersociety Color Council News Letter **26** (December, 1939).

addition of a small amount of yellow, orange, or brown impurity.

The method proposed below is in some respects an extension of that proposed by Davey[3] for identifying crystals by x-ray diffraction patterns, although Davey's scheme is not applicable to the identification of materials which, most commonly, have but a single absorption maximum.

BASIS OF PROPOSED SYSTEM

Four identifying numbers are employed in the proposed system. First place is given to what is ordinarily the most characteristic and unvarying feature of the absorption curve: the number of absorption maxima. The location (wave-length) of the strongest or primary absorption maximum is considered next in importance. If there is a secondary absorption maximum, this is regarded as the third-most-characteristic feature, and if there is a tertiary maximum, this is taken to be the fourth-most-characteristic feature. (We have found that approximately 5 percent of all common, water-soluble dyes have three or more maxima in the visual range.)

Where there are only two absorption peaks (which occurs in approximately 30 percent of all cases), the fourth-most-important datum is considered to be the ratio of the specific extinction coefficients (k) at the two maxima.

Where there is but a single absorption maximum, which is the commonest situation, the location of this maximum is considered to be followed in importance by an indication of the shape in the neighborhood of the maximum. The indication selected is (1) the wave-length of the "right shoulder," the abscissa for which (on the long wave-length limb of the curve) k equals $\frac{1}{2}k_{\max}$, (see Fig. 1) and then (2) the corresponding "left shoulder" wave-length. If one of these is lacking, the other is used, followed by the wave-length of the corresponding "elbow," i.e., wave-length, for which k equals $(1/10)k_{\max}$. Preference is given to "shoulders" over "elbows" as the former are, in general, five-times less affected by small amounts of colored impurities. "Right shoulders" are preferred to "left shoulders" because the former are more "protected;" that is, they tend to be less affected by impurities, impurities being predominantly yellow, orange, brown, etc. Also we have found that effects of irradiation, temperature change, etc., usually affect the "right shoulders" less than the "left."

Additional definitions employed are the following:

Spectral Range

This is ordinarily taken to be 400 to 700 millimicrons, although the system can be adapted to concurrent use of two or more ranges.

Absorption Maximum

This is understood to comprise the primary absorption peak and other peaks for which $k \geq (.1)k_{\max}$. This restriction eliminates relatively weak maxima which might be due to—or at least affected by—colored impurities. In the event that, as the curve approaches the end of the spectral range, the absorption is continuing to increase, the point of intersection of the curve with the range limit is utilized in place of the true, offscale, maximum towards which the curve is tending.

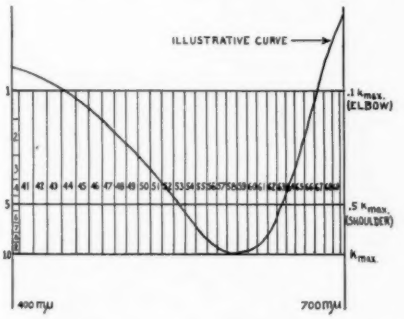

FIG. 1. Form for use in reading off the curve shape symbols. Symbol for illustrative curve is: 1, 58, 63, 53. (Abscissa is linear in log wave-length; ordinate is linear in log log $1/T$).

It has been found most satisfactory to read wave-length only to the nearest 10 millicrons, this providing a good compromise as regards discrimination. Similarly, relative k values ($k/k_{\max}$) are expressed only to the nearest 10 percent. For economy in writing, the third digit in the wave-length is omitted, and the last digit in the relative k value also; for example 90 percent is indicated by the designation *9*.

[3] W. P. Davey, J. App. Phys. **10**, 820–830 (1939).

OBTAINING THE SYMBOL

Having specified the solvent in which the dye has been dissolved and measured, one records the number of absorption maxima, then records the remainder of the symbol as follows:

Case of One Absorption Peak

a. Indicate wave-length of the maximum.

b. Indicate the first of the following wave-lengths which may be evaluated: Wave-length of right shoulder, left shoulder, right elbow, left elbow. If none can be evaluated, which is the case for certain gray or black dyes, use a dash (—).

c. Indicate the second of the above-listed wave-lengths.

Case of Two Absorption Peaks

a. Indicate the wave-length of the primary maximum.

b. Indicate the wave-length of the secondary maximum.

c. Indicate relative k value, secondary maximum vs. primary.

Case of Three or More Absorption Peaks

a. Indicate the wave-length of the primary maximum.

b. Indicate the wave-length of the secondary maximum.

c. Indicate the wave-length of the tertiary maximum.

Working from plots[4] linear in log k (i.e., linear in log log $1/T$), symbols are readily obtained if one has available a transparent form such as is shown in Fig. 1. The form is laid over the test plot and is adjusted vertically until the base line passes through the primary absorption maximum. Wave-lengths of the "shoulders" and "elbows" are then indicated by the points of intersection of the test curve with the $(1/2)k_{max}$ and $(0.1)k_{max}$ lines.

It is to be noted that in obtaining the curve, no particular cell length or dye concentration is required, as the symbols are based entirely on relative values of k. However, since for certain dyes (e.g., formyl violet) Beer's law is not obeyed (even over a dilution range of only 10 to 1), it has proven to be a desirable precaution to use a 1-cm cell and to adjust the dye concentration roughly visually so that the minimum transmission value is between 10 and 30 percent.

TABLE I. Illustrative section from curve shape index (spectral range: 400 to 700 mμ; solvent: water, *p*H 7).

Curve Shape Symbol	Name of Dye
1, 50, 53, 46	Calcochrome Silk White Red B
1, 50, 54, 43	Calcomine Fast Orange 2R
1, 50, 54, 46	Calcocid Scarlet 2R
1, 50, 55, 44	Calcomine Scarlet 4BSY
1, 50, 55, 46	Calcochrome Red No. 650
1, 51, 55, 47	Calcocid Milling Red 3B
1, 51, 56, 46	Calcomine Bordeaux 6BN
1, 51, 56, 47	Calcofast Wool Pink N
1, 52, 57, 45	Calcochrome Alizarine Red SC
1, 53, 56, 47	Calcomine Fast Red 8B

[4] Construction of cams providing log log $1/T$ plots is described in U. S. Patent 2,176,013.

THE INDEX PROPER

The curve shape index itself, as presently used, consists of a tabulation of the symbols arranged (1) by solvent, and (2) numerically, as indicated by the symbol. For each symbol the dye is identified either by its trade name or by manufacturing code number. Table I shows a typical extract from such a tabulation.

USE OF THE INDEX

During a two-year period in which the index has been in use, 2000 entries have been made. It has been found that, for over 80 percent of the entries, but a single dye is referred to. In the remainder of the cases, individual entries refer to two or more dyes, although here the ambiguity can ordinarily be cleared up by referring to the individual curves of the several possibilities, or, if necessary, by following the common procedure of comparing solutions of the dyes in dissimilar solvents.[5] Not infrequently—especially when allowances are made for small variations in curve shape—borderline cases are encountered where two or perhaps three different symbols might be attributed to the curve of the unknown. In such cases, it is necessary to look up the unknown assuming each of the more likely symbols in turn.

[5] E. Zühlke, *Analyze von Färbungen* (Janecke).

Time trials indicate that, in the majority of cases, the symbol for a given curve can be read off in less than a minute, and the tentative identification completed in another minute or two. Final checking against the curves requires another one or two minutes.

MIXTURES

When the unknown is a mixture of two or more dyes having rather similar curve shapes, it is, of course, not possible ordinarily to make the identification directly. Thus chromatographic analysis or other procedures outside the scope of the present article are resorted to.

In certain cases, however, the identification of mixtures can be carried out directly using the curve shape index and the file of reference curves. Thus, for example, if a mixture has a curve comprising two fairly well-separated absorption maxima and if it is suspected that each of these may be due to a different component dye, then the symbol for each peak may be obtained as though the other peak were not present, perhaps with some estimation of the effect of one peak on the other (Fig. 2). Where one peak is not very pronounced, as when the second component is present only in small amount, it may often be disregarded entirely in the attempt to identify the other (major) component.

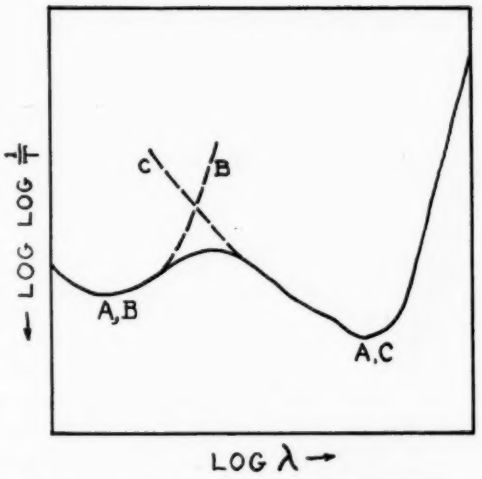

FIG. 2. Analysis of two-component mixture. The experimental curve *A* is roughly "separated" into the component curves *B* and *C*, for each of which a separate identification is attempted.

LIMITATIONS

The curve shape index has the following limitations:

1. Its discrimination is not adequate for distinguishing curves of fairly similar shape. Thus, for example, blacks, grays, and browns cannot always be identified simply.

2. It cannot ordinarily be used to make direct identifications of the components of a dye mixture.

3. Borderline cases of curve shape are encountered, such that either of two symbols may appear equally valid. In some cases, there may be doubt as to the number of absorption peaks, this being most common for irregular curves generally horizontal in trend.

The writer is indebted to Mr. C. F. Pinzka for his assistance in the work.

A New Large Two-Lens Quartz Spectrograph of Compact Design*

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(Received November 13, 1941)

ADVANTAGES OF THE TWO-LENS DESIGN

THE large Littrow Quartz Spectrograph has been in use for well over twenty years, and while improvements in the mechanical design have been made from time to time, the changes in the optical construction have been relatively few. The scattered light has been somewhat reduced by the substitution of evaporated aluminum for the tinfoil amalgam earlier employed as backing for the 30° quartz prism, and also by the removal of the right-angle quartz prism to a point outside of the spectrograph proper.

Nevertheless, the elimination of the light reflected from the lens surfaces has always presented difficulties: either the lens must be masked to an extent depending on the length of the slit employed, with resulting loss of aperture, or it must be tilted considerably with consequent loss of definition.

The prospect for improvement by the use of coated surfaces on the lens is not good. These coatings must be $\frac{1}{4}$ wave thick, and the wavelength varies from 2000 to 8000A.

In smaller quartz spectrographs the two-lens type has been most used owing to these and other considerations, and one naturally asks why the two-lens design has been little used in the large sizes. There are two main reasons. First, the plate is so far removed from the slit that two operators are required. Second, the problem of shifting from one section of the spectrum to the other is not readily solved. One has to swing the plate about a center two meters away, and in addition to slide the plateholder and slit toward the prism, or else separate the prism and lenses by considerable distances. Nevertheless, a spectrograph on these lines was made some years ago by J. S. Foster.[1]

Apart from the difficulty arising from reflected light, the Littrow design is more likely to show astigmatism and doubling, as it is impossible for both the slit and the plate to be on the axis of the lens, and it is likewise impossible for the light to traverse the prism at minimum deviation, i.e. along the crystallographic axis. Using a 10-inch plate, the two-lens design has only $\frac{2}{3}$ the astigmatism of the Littrow, while with a 14-inch plate it has only $\frac{1}{3}$ as much.

A point of some importance also is that even after the most careful selection of quartz has been made, we must use that with which nature has favored us. No quartz is absolutely homogeneous, and in the Littrow design the resultant errors of focus are doubled by the fact that the same optical elements are traversed twice. The same applies to any residual errors in the figuring of the optical surfaces.

OPTICAL ARRANGEMENT OF NEW LARGE TWO-LENS QUARTZ SPECTROGRAPH

In order to save space and at the same time to make possible the adjustment of the instrument for various sections of the spectrum, a front surface aluminum mirror is introduced between the camera lens and the plate in the manner shown in Fig. 1. This figure in addition shows the use of the instrument with an exit slit as a large monochromator for the photoelectric measurement of lines or monochromatic bands. With this arrangement of mirror, prism and lenses, the slit and plateholder come into very convenient positions, and the illuminating bench is conveniently accessible from the plate end without any further right-angle prisms. This is shown in Fig. 2.

Another possible arrangement with prism and mirror between the lenses, similar to the Wadsworth design, was not employed because of the impossibility of compensating the optical rotation of the lenses with this arrangement.

AUTOMATIC ADJUSTMENT OF THE COMPONENT PARTS

The number of elements involved and their mutual relation presented the problem of secur-

* Presented at the Ninth Summer Conference on Spectroscopy and Its Applications, Massachusetts Institute of Technology, Cambridge, Massachusetts, July, 1941.

[1] J. S. Foster, "A quartz spectrograph for the examination of biological material," Can. J. Research **A14**, 173–176 (1936).

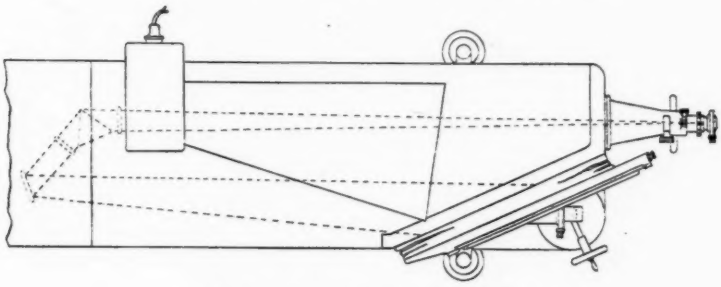

FIG. 1. Schematic view of instrument.

ing the necessary coordination of their positions. The first instrument, in fact, was made fully automatic, with one handle serving to change the range of spectrum covered by the plate. It was decided to adopt the condition of minimum deviation as fundamental in order to avoid trouble from doubling over the extended plate, which it was decided to make 14 inches long. With this length of plate, the spectrum from 2000 to 8000A can be covered on two plates. On the other hand, the range 2200 to 3400A can be covered on a single plate, as can also the range between 2500 and 5900A.

The conditions which we aim to satisfy are as follows:

(1) The slit shall remain on the collimator lens axis in all positions of the collimator lens.

(2) The collimated wave-length λ shall traverse the prism at minimum deviation.

(3) The camera lens axis shall remain on the emergent ray of wave-length λ.

(4) The mirror shall in every position reflect the wave-length λ to the center of the plate, and while turning shall so position itself that the distance from the camera lens to the mirror to the center of the plate measured along the ray shall be equal to the distance from collimator lens to slit. This keeps it in focus.

(5) The tilt of the plate shall be the same as that of the spectrum.

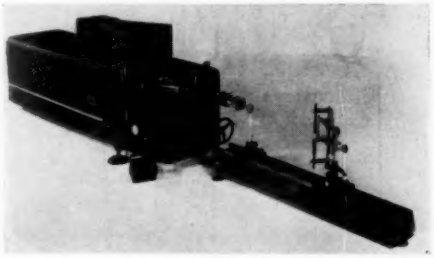

FIG. 2. Complete spectrograph with illuminating bench.

FIG. 3. Side view of optical train.

The above conditions can all be met in a rather straightforward manner, except condition (4), for which an approximate solution was effected as follows. The mirror position on the refracted ray was determined to give the required distance sum for two wave-lengths (0.384μ and 0.193μ), and the angular setting of the mirror was then deduced. From the difference of angle between these two settings, the length of arm supporting the mirror and its center of rotation were determined. It is clear that by suitable rotation of the mirror with the help of a cam, it is possible for every collimated wave-length to reflect the ray to the center of the plate, but we have no assurance that the distance sum will come out right for any but the now chosen wave-lengths. As a matter of fact, however, the error is quite negligible, in no case greater than 0.06 mm.

DETAILED CONSTRUCTION

Figure 3 shows the important parts of the detailed construction of the optical train. The

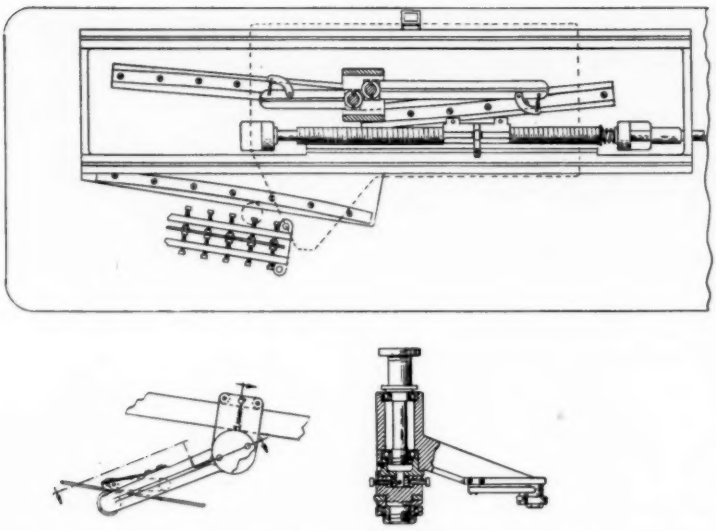

FIG. 4. The cams and arms (above); and (below) the differential correcting device.

entire train is mounted on a carriage which focuses through a range of about 14 inches on a bed with straight ways. The focusing is effected by means of a screw operated from a hand-wheel situated below the slit tube. The bed carries three solid cams for the prism, camera lens, and mirror arm, respectively. Since the ratio of the angular travel of prism and lens is 1 : 2, duplicate cams are employed with lever arms in the ratio of 2 : 1. The lens is mounted on a yoke between ball centers, and the prism is mounted on a fork also between ball centers. The center of rotation of the lens arm is at the intersection of the optical axes of the two lenses. The center of rotation of the prism, however, is offset to keep the prism faces always central with respect to both lenses. The aluminized mirror is mounted in a fixed position on a 16-inch arm. This rotates on a ball bearing shaft, and is further supported by a roller under the mirror, working on a flat bearing surface. The appearance of the optical train will be clear from Fig. 3. The purpose of the flexible cam will be described shortly.

Figure 4, upper part, is a schematic view of the ways, focusing screw and nut, the three solid cams, and the flexible cam, showing the arms attached to the lens and prism supports and the springs for holding them in contact with the ways. These springs are so designed as to exert no resultant side thrust on either the cams or the carriage. The lower part of Fig. 4 shows the construction of the differential correcting mechanism actuated by the flexible cam.

DIFFERENTIAL CORRECTING MECHANISM

Instead of being mounted directly on the mirror arm in the fashion employed with the lens and prism arms, the bearing roller is mounted slightly offset on a sleeve revolving on ball

FIG. 5. The plate tilt cam.

FIG. 6. The plateholder end.

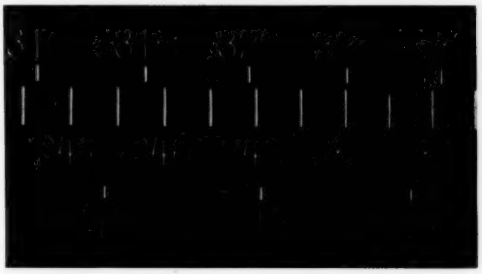

FIG. 7. The wave-length scale.

bearings around a shaft integral with the mirror arm. The sleeve carries an arm which is pressed by a counter-roller against the surface of the flexible cam. There is thus no net side thrust on the flexible cam, nor indeed on the fixed cam, nor on the carriage. If the flexible cam is so shaped that it does not turn the sleeve on the shaft, obviously the fixed cam alone will govern the motion of the arm. But if the flexible cam rotates the arm, an additional displacement, which puts a differential correction on the mirror position, is given to the arm.

In actual practice it was found satisfactory to arrange the amount of offset so that 1-mm displacement of the flexible cam effected a differential correction of 1/20 mm.

The differential correcting mechanism provides means for empirically improving on the calculated settings or compensating any errors of manufacture or adjustment.

PLATEHOLDER TILT MECHANISM

Figure 5 shows an inside view of the plateholder bracket. The drive shaft of the focusing screw carries a worm actuating a worm gear, on which is mounted a spiral cam. An arm protruding through from the plateholder slide carries a roller bearing against the face of the spiral cam. Also seen protruding from this bracket is a clamp for arresting the rotation of the focusing screw. Attention is also called to the Solenoid operated shutter, which admits light from the slit tube into the instrument proper.

Figure 6 shows the plateholder slide from outside the spectrograph. The slide rotates on a ball bearing turret, the center of which is directly below the center of the plate. In this figure will be noticed the hand wheel for moving the plate up and down, and the handle of the clamp which arrests the rotation of the focusing shaft. The tape under tension above the slide supports the weight of the latter. In the extreme lower right of the figure is seen a small correcting button for improving the tilt of the plateholder.

At the top of Fig. 6 is seen the lower part of the screen on which the wave-length scale is projected.

Figure 7 shows a portion of this scale. The upper and lower scales represent, respectively, the long and short wave limits covered by the 14-inch plate. The central scale shows the wavelengths on the center of the plate, which constitutes a convenient and accurate point of reference for purposes of identification, for fluorescent screen, exit slit, or for reference in case other lengths of plate are employed.

We have found that the vapors given off by certain commonly used lacquers can black out the far ultraviolet part of the spectrum. A spectrograph should therefore be ventilated occasionally. On the present instrument we have included some nipples for flushing out the spectrograph with nitrogen. However, without such help we have obtained good densities with the 1862 line of aluminum in two minutes, using a 1-kw 25,000 v condensed spark and Eastman III-B-UV plates.

X-Z Planes in the 1931 I.C.I. System of Colorimetry[1]

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(Received January 2, 1942)

THE Maxwell triangle[2] usual in colorimetry is predicated on a symmetrical relationship among the three components of the Young-Helmholtz theory of color vision. There is no reason to treat them symmetrically: the Munsell color system is one of cylindrical coordinates about the axis of "value;" the 1931 I.C.I. system attaches all the luminosity to the Y component, and observations of chromaticity differences are made after equating brightness.

Uyterhoeven[3] has published an equilateral triangular diagram for the I.C.I. Standard Observer, and also an isosceles right triangle with y plotted against z. The more familiar diagram of Judd[4] is also an isosceles right triangle, but with y plotted against x. Since Y is the unique coordinate, a plot of z against x (see Fig. 1), would seem more logical.

Any chromaticity diagram is a radial projection, onto a suitably oriented plane, of some three-dimensional tristimulus diagram. A stereoscopic view of the "equal-energy" spectrum locus is given in Fig. 2. In this figure the line for I.C.I. Standard Illuminant C is toward the observer, and $\bar{z}$ has been plotted on a scale 3-fold smaller than $\bar{x}$. Distances in front of the X–Z plane are proportional to $\bar{y}$.

If the tristimulus values have been plotted to equal scales on mutually perpendicular axes, the radial projection onto the (111) (octahedral) plane cutting off equal intercepts on the three axes can be converted from an equilateral to an isosceles right triangle by parallel projection onto any one of the three coordinate planes.

UNIQUE CHROMATICITIES

The so-called equal-energy stimulus is one of five unique chromaticities, and perhaps not the most significant of the five. These five chromaticities are listed in Table I and specified in terms of I.C.I. trichromatic coefficients, in terms of the equal-energy basic stimulus, and in terms of I.C.I. Standard Illuminant C (see section "The Chromance Diagram" for an explanation of the symbols X_c, Y_c, Z_c).

THE "CHROMANCE" DIAGRAM

By plotting the tristimulus values X and Z for colors of the same luminous reflectance, Y, (albedo, lightness, Munsell value) it is found that a suitably chosen ratio of scales[5] gives a nearly uniform radial and circumferential spacing of the Munsell colors, centered about the neutral color of equal value.

The color samples in the *Munsell Book of Color*[6] have been chosen for testing the suitability of the methods of plotting to be suggested in this paper for three reasons: (1) The years of effort to equalize introspectively the intervals of hue, of value and of chroma give assurance that the

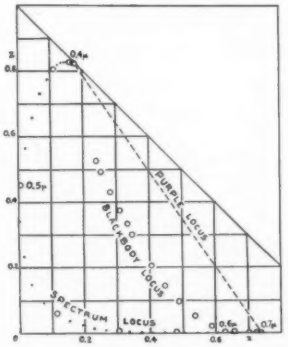

FIG. 1. I.C.I. (equal-excitation) chromaticity diagram with x and z plotted at right angles.

[1] An amplification of a paper presented at the Rochester meeting of the Optical Society of America, October 5, 1940, J. Opt. Soc. Am. **30**, 657 (1940); see also S. M. Newhall, J. Opt. Soc. Am. **30**, 619–620 (1940).

[2] Credited by Maxwell to Thomas Young, *Scientific Papers of James Clark Maxwell* (1890) Vol. 2, p. 272, reprinted from Proc. Roy. Inst. (1871).

[3] W. Uyterhoeven, *Elektrische Gasentladungslampen* (Julius Springer, 1938), Figs. 83, 84, pp. 168, 170.

[4] D. B. Judd, J. Opt. Soc. Am. **23**, 364 (1933), Fig. 2.

[5] This scale factor varies not only from observer to observer—as will be evident from the existence of color-weak as well as color-blind observers—but from point to point on the retina of the same observer, as shown by the change in apparent hue in passing from the fovea to the periphery of the retina. J. W. Baird, *The Color Sensitivity of the Peripheral Retina*, Carnegie Institution of Washington Publication No. 29 (1905).

[6] Munsell Color Company, Inc., Baltimore, 1929.

TABLE I. Unique chromaticities.

Uniform Distribution of	alternatively of
1. Energy with wave-length	Quanta with wave-length squared
2. Energy with log wave-length	Quanta with wave-length
3. Energy with frequency	Quanta with log wave-length
4. Energy with frequency squared	Quanta with frequency
5. Energy with frequency cubed	Quanta with frequency squared

∞ Blackbody at infinite temperature

	x	y	z	$X/Y=x/y$	$Z/Y=z/y$	X_c/Y_c	Z_c/Y_c	Color Temp.*
1.	0.3333	0.3333	0.3333	1.0000	1.0000	1.0200	0.8467	5640°K
2.	.3071	.3107	.3822	0.9883	1.2301	1.0080	1.0415+	7280°
3.	.2824	.2861	.4315+	.9872	1.5084	1.0069	1.2772	10280°
4.	.2959	.2602	.4799	.9986	1.8439	1.0186	1.5613	18200°
5.	.2399	.2341	.5260	1.0246	2.2464	1.0451	1.9020	∞

* Color temperatures for these non-blackbody chromaticities were estimated by drawing normals to the blackbody locus on a plot of Z_c/Y_c against X_c/Y_c (scale factor 2½) and reading reciprocal temperature from a plot of Z_c/Y_c against reciprocal temperature for blackbodies. They will, of course, differ from estimates based on other types of "uniform-chromaticity-scale diagram."
D. B. Judd, J. Opt. Soc. Am. **25**, 24 (1935); D. L. MacAdam, J. Opt. Soc. Am. **27**, 294 (1937); F. C. Breckenridge and W. R. Schaub, J. Opt. Soc. **29**, 370 (1939); see also W. D. Wright, Proc. Phys. Soc. **53**, 93 (1941).

spacing of the Munsell colors on a diagram will be a dependable indication of the psychological utility of the diagram; (2) the spectrophotometric measurements already made by Glenn and Killian[7] and other measurements now in progress at the National Bureau of Standards, ensure that the Munsell colors can be accurately located on any diagram based on the 1931 I.C.I. Standard Observer; and (3) the Munsell colors are commercially obtainable both in book form and as separate samples.

The Munsell color notation is based on five equally-spaced principal hues, called red, yellow,

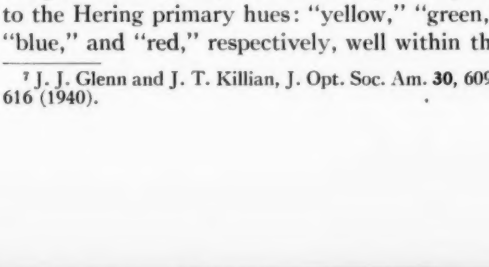

FIG. 2. Stereoscopic view of equal-energy spectrum in I.C.I. tristimulus space.

green, blue, and purple. The alternative system of designating hues by numbers from 1 to 100 starts with the hue $10RP = RP - R = 100$, so that the numbers 25, 50, 75, and 100 (Munsell designations: *Y*, 10*G*, *PB* and 10*RP*) correspond to the Hering primary hues: "yellow," "green," "blue," and "red," respectively, well within the precision to which either the Munsell principal hues or the Hering primaries are established.

The tristimulus values (called X, Y and Z) published by Glenn and Killian[7] for the colors in the *Munsell Book of Color*[6] are computed for illumination by I.C.I. Standard Illuminant *C*, but are on the basis of the equal-energy stimulus, i.e., of a distribution of energy uniform with respect to wave-length. This is tantamount to taking as the standard of reflectance a fictitious surface which when illuminated by Illuminant *C* would reflect an equal-energy spectrum of luminous value equal to the incident radiation.

Since the perfect diffuse reflector is a physically neutral surface whose reflectance is the same (unity) at all wave-lengths, tristimulus values relative to the illuminant can be obtained by dividing the values of Glenn and Killian by the tristimulus values for I.C.I. Standard Illuminant *C*. These quotients may be designated:[8]

$$X_c = 1.01998X, \quad Y_c = Y, \quad Z_c = 0.84672Z,$$

For any physically neutral surface $X_c = Y_c = Z_c = \rho_\lambda = \rho$. Hence the differences $X_c - Y_c$, $Z_c - Y_c$

[7] J. J. Glenn and J. T. Killian, J. Opt. Soc. Am. **30**, 609–616 (1940).

[8] The standard symbol of the Illuminating Engineering Society for "reflection factor" is ρ. On that basis the quotients would be respectively ρ_x, ρ_y, and ρ_z; their differences $\rho_z - \rho_y$, $\rho_z - \rho_y$; their ratios ρ_x/ρ_y, ρ_z/ρ_y.

$X \equiv \int \Phi_\lambda \bar{x} \rho_\lambda d\lambda / \int \Phi_\lambda \bar{y} d\lambda$, $X_c \equiv \rho_X \equiv \int \Phi_\lambda \bar{x} \rho_\lambda d\lambda / \int \Phi_\lambda \bar{x} d\lambda$,
$Y \equiv \int \Phi_\lambda \bar{y} \rho_\lambda d\lambda / \int \Phi_\lambda \bar{y} d\lambda \equiv Y_c \equiv \rho_Y$,
$Z \equiv \int \Phi_\lambda \bar{z} \rho_\lambda d\lambda / \int \Phi_\lambda \bar{y} d\lambda$, $Z_c \equiv \rho_Z \equiv \int \Phi_\lambda \bar{z} \rho_\lambda d\lambda / \int \Phi_\lambda \bar{z} d\lambda$.

X_c, Y_c and Z_c are the mean ordinates obtained from spectrophotometric curves for reflection samples by the method of selected ordinates.

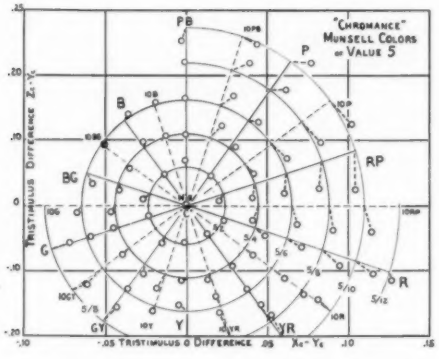

FIG. 3.

will be zero for such a color.[9] On a plot of $Z_c - Y_c$ against $X_c - Y_c$ the neutral color of any value (luminous reflectance) will lie at the origin of coordinates, surrounded at increasing distances by the colors of increasing chroma (saturation). On such a "chromance diagram" for colors of equal value, distances along any radius from the origin are proportional to *colorimetric* purity. See Fig. 3[10] for a chromance plot of colors of Value 5, (with a scale factor of $2\frac{1}{2}$).

CHROMATICITY AS RELATED TO THE CHROMANCE DIAGRAM

The appearance of a color sample, with standard surroundings receiving the same illumination as it does, is not much altered by considerable quantitative changes in the illumination. For a sample with completely dark surroundings, the luminous reflectance loses much of its significance, and as in the evaluation of a source of illumination, a chromaticity diagram comprises the most significant information. The Maxwell triangle[2] and its rectangular equivalents are chromaticity diagrams, but they are not the only chromaticity diagrams which can be based on the 1931 I.C.I. Standard Observer.

The ratios X_c/Y_c and Z_c/Y_c depend only on the chromaticity of the sample. A plot of these two ratios may therefore be referred to as a "constant-brightness chromaticity diagram." For a group of samples of identical luminous reflectance (Munsell value) such a plot (see Fig. 4) will be geometrically similar to the "chromance diagram" of Fig. 3. It follows that radial distances on the former will likewise be proportional to *colorimetric* purity. The ratio of the sizes of the two types of diagram will differ for colors of different value, and colors of equal hue and chroma but unequal value will not coincide on either type of plot.

In plots of the chromaticity of reflection or transmission samples, the logical basis of reference is the chromaticity of the illuminant (actual or constructive, as in computations based on spectrophotometric curves). In the case of sources, there is no such unique basis of reference. In general, since the data for the 1931 I.C.I. Standard Observer are given in terms of wavelength, it will be simpler to refer data on the chromaticity of sources to the equal-energy basic stimulus, i.e., to plot Z/Y against X/Y. Figure 5 shows a portion of the spectrum locus, the blackbody locus, and a number of fluorescent lamps, plotted on that basis.

THE CHROMATIC-VALUE DIAGRAM

While there is a one-to-one relation between luminous reflectance (albedo) and Munsell value (lightness), the relation is not a mathematically simple one for the conditions[11] under which the

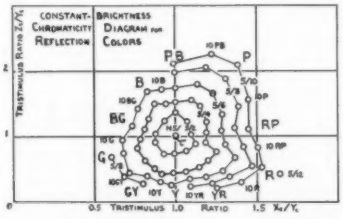

FIG. 4. Constant-brightness chromaticity diagram for Munsell colors of value 5.

Munsell colors are compared. Munsell, Sloan, and Godlove[12] determined empirically a value (lightness) function on which the present Munsell colors are based. If this function be applied to all

[9] It will be evident that this will be true for any other standard illuminant, and that any nearly neutral color will have nearly the same coordinates under various near-white illuminants (color-constancy).

[10] Cf. Fig. 1d, S. M. Newhall, J. Opt. Soc. Am. **30**, 620 (1940), in which the Glenn-Killian tristimulus values have been plotted with a scale factor of 3.

[11] For a constant state of adaption, E. Q. Adams and P. W. Cobb, J. Exper. Psychol. **5**, 39–45 (1922), derived the equation, $S = B/(B+B_0)$. For samples of finite size, and finite times of presentation, the state of adaption cannot be expected to be uninfluenced by the samples.

[12] A. E. O. Munsell, L. L. Sloan, and I. H. Godlove, J. Opt. Soc. Am. **23**, 394, 419 (1933).

three components of reflectance, $\rho_X \equiv X_c$, $\rho_Y \equiv Y_c$, $\rho_Z \equiv Z_c$, the resulting V_X, V_Y, V_Z will uniquely define any color. V_Y is the Munsell value (lightness) and the differences[13] $(V_X - V_Y)$, $(V_Z - V_Y)$ will be zero for a physically neutral (achromatic) color. For a chromatic color they may be designated collectively as "chromatic value."

These subtractions are the mathematical representations of the inhibitory nerve connections (synapses) in the retina, postulated in the author's theory of color vision.[13] Figure 6 shows the assumed nerve connections in normal vision, together with symbols relating the colorimetric magnitudes to the several nerve elements.

Radiant power whose wave-length distribution is defined by Φ_λ is evaluated[4,14] by the rod and cone elements of the retina as S, X, Y, Z, where X, Y, Z, are the I.C.I. tristimulus values, and S is the corresponding integral for rod vision

$$S = \int \Phi_\lambda \bar{s} d\lambda.$$

Dependent on the state of adaption of the eye, these quadristimulus values are transformed to nerve responses symbolized by V_S, V_X, V_Y, V_Z. The Munsell value (lightness) function[12] is assumed to be correct for all four transformations.

Beyond the inhibitory synapses (indicated by minus signs) the signals proceeding to the brain

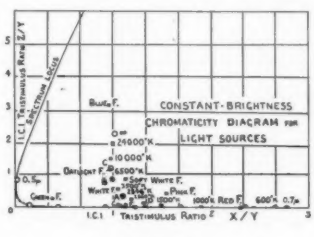

FIG. 5.

are proportional to the differences $V_X - V_Y$ and $V_Z - V_Y$. The scale factor[5] found necessary to make the lines of constant chroma circles on the chromatic-value diagram indicates that the factor of proportionality is not the same for the two chromatic components.

[13] Psychol. Rev. **36**, 56–76 (1923), especially Fig. 1, p. 59.
[14] E. Q. Adams, "A Proposal for the Specification of Scotopic Luminosity," J. Opt. Soc. Am. **31**, 757 (1941).

A consideration of the possible ranges of the components of chromance and chromatic value for reflection colors suggests that the observed difference in proportionality factors agrees well with the "volume control" ratio necessary to make full use of the transmitting capacity of the fibers of the optic nerve.

On account of the greater overlap of the $\bar{x}$ and $\bar{y}$ distribution functions, the maximum value of the component of chromance $|X - Y|$ is less than

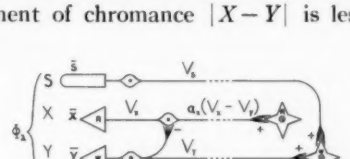

FIG. 6. I.C.I. colorimetric magnitudes as related to nerve elements postulated in Adams theory of color vision.

that of the component $|Z - Y|$. For illumination by the equal-energy basic stimulus, the values are

$$\pm(X - Y)_m = 0.3923$$
$$\pm(Z - Y)_m = 0.8913 \quad \text{ratio} = 2.27.$$

For illumination by I.C.I. Standard Illuminant C

$$\pm(X_c - Y_c)_m = 0.4013$$
$$\pm(Z_c - Y_c)_m = 0.8843 \quad \text{ratio} = 2.20.$$

For these colors of maximum *chromance*, the ranges of chromatic value are

X_c	Y_c	V_X	V_Y	$V_X - V_Y$
0.7555	0.3542	9.11	6.72	+2.39
0.2445	0.6458	5.73	8.61	−2.88
			Spread	5.27

Z_c	Y_c	V_Z	V_Y	$V_Z - V_Y$
0.9504	0.0660	9.86	3.15	+6.71
0.0496	0.9340	2.74	9.80	−7.06
				13.77

Ratio = 2.61.

The maximum spread of *chromatic value* will be slightly greater than this, but the ratio will probably be approximately 2.6. Actual reflection colors lie well inside the ranges of the ideal (MacAdam) colors for which these calculations have been made. Since the range of V_Y for reflection colors is, by definition, from 0 to 10, the chromatic components would need, respectively, to be increased 90 percent and reduced 28 percent, i.e., $\alpha_X = 1.90$ and $\alpha_Z = 0.72$.

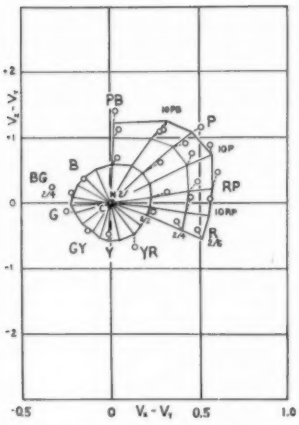

FIG. 7. Chromatic value of Munsell colors at value level 2.

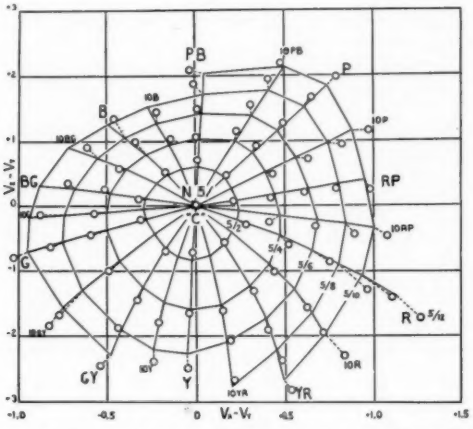

FIG. 10. Chromatic value of Munsell colors at value level 5.

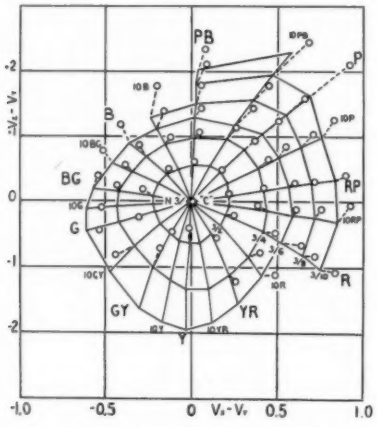

FIG. 8. Chromatic value of Munsell colors at value level 3.

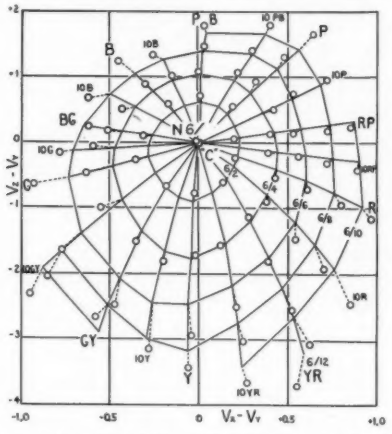

FIG. 11. Chromatic value of Munsell colors at value level 6.

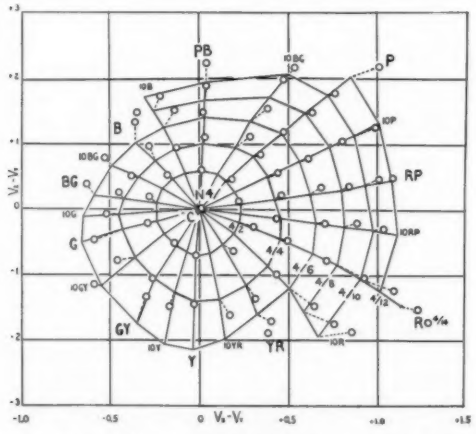

FIG. 9. Chromatic value of Munsell colors at value level 4.

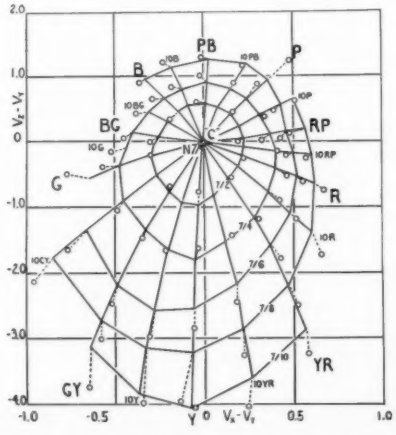

FIG. 12. Chromatic value of Munsell colors at value level 7.

Since the relative number of X- and Z-fibers is also a factor, these calculations suggest that, in the fovea, the two sorts are approximately equal in number, for a normal trichromatic observer.

The chromatic value of the colors in the Munsell *Book of Color*, based on the spectrophotometric measurements and calculated tristimulus values of Glenn and Killian[7] is shown in Figs. 7 to 13. These figures give also smoothed chroma contours, equivalent to those shown on I.C.I. (x, y)-diagrams by S. M. Newhall.[15] The author is indebted to Miss Dorothy Nickerson, color technologist of the Agricultural Marketing Service of the United States Department of Agriculture, for permission to use these figures, and for checking his calculations of chromance, (constant-brightness) chromaticity, and chromatic value.

While the agreement for colors of the same Munsell hue and chroma, but different value, is far from perfect, the scatter is small enough to warrant the hope that colors more uniformly spaced, and measured under the same illuminant as that under which they were painted, will be found to agree in chromatic value within the error of measurement.

[15] S. M. Newhall, J. Opt. Soc. Am. **30**, 639–42 (1940), Figs. 7 to 13.

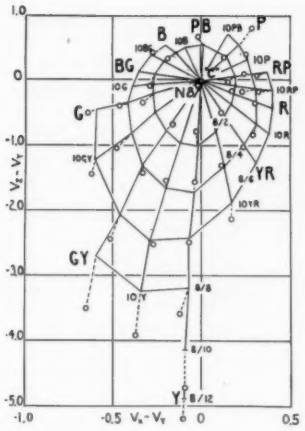

FIG. 13. Chromatic value of Munsell colors at value level 8.

If such an agreement is not found, the question will arise whether a refinement of the value function, or of the data for the I.C.I. Standard Observer—to bring one or both into better agreement with the group of observers on whom the Munsell colors are based—would bring the Munsell hue and chroma, on the one hand, and the chromatic value on the other, into point-for-point agreement.

Some Characteristics of Metal Mirrors and a New Gonioreflectometer

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(Received January 29, 1941)

A study of the reflection characteristics of over a hundred mirrors of thirty-seven kinds has been made to get data that will permit both a comparison of mirrors and of the various methods and instruments for testing them. Tests were made of specular reflectance at angles from 15 degrees to 82.5 degrees and a new gonioreflectometer was built particularly for this work. The angular distribution data were used to compute average reflectances, and this was done in three different manners that represent three different points of view as to what average reflectance means. A number of alloys of aluminum were made and tested in an endeavor to improve on pure aluminum, and the entire group of mirrors was retested a number of times to determine the degree of permanence of the various metals.

PREPARATION OF GLASS

THIS work was initiated to get data on certain alloys of aluminum that were reported to give superior results when evaporated on glass. It was found that there was much to be learned about the technique of preparing both the metal and the glass, and that the evaporating process required considerable study before consistently good results could be obtained. In addition to the evaporated metal mirrors, which were tested on both the first and second surfaces, a number of plated and solid metal mirrors were studied for the sake of any comparisons that might be desired.

The cleaning and handling of the microscope slides (1 in.×3 in.×0.04 in.) required careful preparation and execution; otherwise defective mirrors resulted, and these defects often did not become visible until several weeks had elapsed.

In preparing the glass for plating three things must be guarded against. These are oil from the hands of the workman, deposits from the washing water, and dust from the air and objects that may touch the slide. The glass was first washed with "shamva" magnesium oxide in distilled water, using a dust-free cotton swab on a stick. A second washing was done in distilled water with another cotton swab, and all handling was with tweezers. For rinsing a beaker was filled to overflowing with distilled water and the surface swept clean with a glass bar. The cleaned glass was dipped several times in this to remove the last trace of the oxide, and the slide was then held on edge with tweezers to drain, the last drop being removed with a wire.

The dry slide was next inspected under strong projected light for adhering dust or scratches and then stored in a dust-free cloth until needed.

A number of variations from the above procedure were tried, such as using potassium dichromate with sulphuric acid as a cleaning agent, but the "shamva" was the most satisfactory.

EVAPORATION OF METAL

Preliminary tests have indicated that a high vacuum is not necessary in the evaporation process, and in fact, it has been reported that pressures of inert gas up to 10μ have a beneficial effect. The benefit, if any, is small and pressures of 0.01μ and less were used largely to get rid of water vapor.

The evaporating equipment consists of a bell jar 9 in. in diameter and 24 in. high and a detachable inner jar that may be removed and freed of adhering metal. The evaporating filament is tungsten in the form of an inverted V near the top of the jar. A platform under the filament holds the glass to be plated, if only three or four mirrors are to be made at one time. However, if a bigger batch is wanted, a semicircular holder is placed on the platform. One slide which is held projecting above the holder is used by the operator as a control. The filament is watched through this slide until the thickening deposit makes it vanish. This takes about twenty seconds, and an additional ten seconds is given to insure complete opacity.

FIG. 1. The rotatable part of the gonioreflectometer is seen to consist of a metal drum with a peripheral slit covered with a hanging strap of black velvet. The thumb tacks on the stationery base mark 15-deg. steps in mirror incidence and reflection and 30-deg. steps in rotation of the drum.

FIG. 2. This view of the gonioreflectometer shows the lamp house at the right within the drum, the block of magnesium carbonate that serves as a target and in the center of the drum, the mirror holder. The instrument is here set for an angle of incidence of 60 deg.

A new filament was used for each operation of the jar even when consecutive runs were with the same metal. The charging metal was attached to the tip of the V, and while surface tension held the metal within the sides of the point, there was always a film spread over the entire filament.

To obtain tungsten and molybdenum mirrors these metals were made up of straight filaments and mounted on the axis of tubular bulbs. The glass to be coated was laid parallel to the filament which was burned at a high temperature for several days until the deposit became thick enough to be opaque.

In spite of all the precautions taken to keep the filament and charge clean, there is likely to be adhered grease and dirt. To eliminate these impurities a movable shield was placed over the filament and left there until the surface of the molten charge seemed clean and free from surface marks that would indicate impurities. Once the molten drop was clean the shield was removed by means of an external magnet, and the coating process began.

The completed mirrors were found to be rather hot (about 180°C) at the end of the process, and instead of waiting several hours for them to cool by radiation, a charge of cold nitrogen was admitted into the jar. This cooled the mirrors rapidly and possibly had a beneficial effect in slowing up the action of oxygen and water once the jar was opened to the atmosphere.

GONIOREFLECTOMETER

The instrument built to take photometer readings at definite angles of incidence and reflection consists of a drum mounted on a turn-

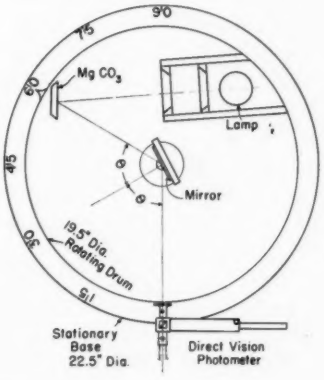

FIG. 3. This sketch shows how the magnesium carbonate target receives constant illumination and is always viewed along a radial line. The mirror is turned by hand at each setting to bring the center of the target into the center of the photometer field.

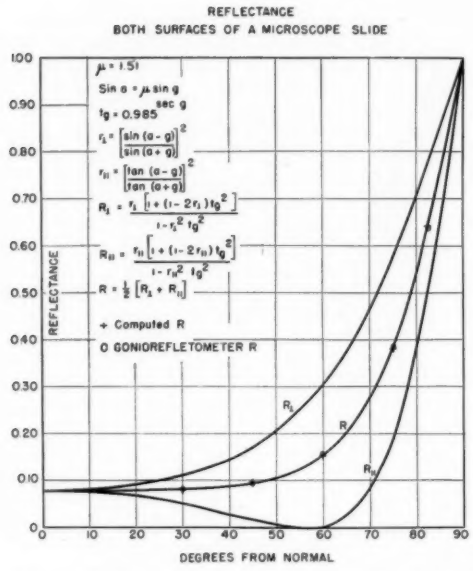

FIG. 4. These reflection curves were computed from measured values of index and absorption of a microscope slide similar to the slides used to make the mirrors. A careful test with the gonioreflectometer was made to detect possible systematic errors in the instrument. The agreement between computed and test values indicate that the errors are negligibly small.

table calibrated in degrees and having a slot extending around its periphery through which a photometer can be pointed. An external view, Fig. 1, shows the method of attaching the photometer in a fixed position, and also the strip of black velvet that drops over the peripheral slot. A tube in front of the photometer raises the velvet and permits a view of the interior while the drum is being rotated. In Fig. 2 the cover is removed to show the lamp house at the right, a magnesium carbonate block on the far side, and the mirror holder in the center of the drum. Since lamp housing and carbonate are fixed with respect to one another the illumination is constant, and the line of observation is also constant from the center of the instrument, where the test mirror is located, along a radial line to the carbonate. The line of sight is also a radius from photometer to mirror, and at each setting of the drum the mirror mount is turned by hand until the carbonate is brought into the photometric field.

A lens was placed over the nose of the photometer serving the double purpose of restricting the width of the field to about a quarter of an inch at the mirror, and imaging a neutral object plane into the plane of vision of the eyepiece. With this arrangement any dust particles or minor defects on the mirror or carbonate were blurred and did not interfere with the uniformity of the photometric field.

A mirror is shown mounted over the center of a pintle in Fig. 3, and the centering device, which consists of a nail in the end of a hinged board (not shown) is arranged to swing up in front of the carbonate. When this is turned into a nearly vertical position the shadow of the head of the nail falls on the center of the carbonate. This point can be brought accurately into the center of the photometric field by rotating the mirror on its pintle.

Two people ordinarily operate the gonioreflectometer, one to hold currents on the two lamps, read the photometer and keep the records, while the other changes and adjusts the mirrors and balances the photometer.

The gonioreflectometer was critically checked by testing a bare microscope slide that had been tested for refractive index (1.51) and for transmission (0.985) in a normal direction. From these two figures the data of Fig. 4 were computed. The computed and test points are in agreement and there is no indication of systematic errors in the instrument.

The color temperature of the lamps was about 2450°K. No color correcting filters were used except when measuring gold and copper and then only a partial color correction was made. There was a noticeable change in the color of light reflected from gold and copper as the angle of observation was changed. At low angles the color was distinctly yellow while at 82.5 degrees it was closely that of the carbonate.

VARIATION OF REFLECTANCES WITH ANGLE

The reflectance of a metal mirror varies with the angle of incidence and is a complicated function of both the refractive index μ and the extinction coefficient k. Since μ is variable with angle, the reflectance is much more easily measured than computed.

The optical design of the photometer is symmetrical with respect to the two polarization

components of the reflected light, and hence, the given data are the average of the two components in every case and no attempt is made to separate them.

The mirrors here presented are in many cases only the best samples. They were usually made in groups of four, and all four were used or rejected as a group, depending on how it compared with other groups. The rule was adopted because small variations among members of the same group seem to be at present an unavoidable feature of the process. Variations among groups are more likely to be due to changes (intentional and otherwise) in the process. It is felt that anyone else doing this work can at least equal these results and probably improve on them. The best groups are therefore assumed to represent most fairly the properties of the various mirrors.

The variation of reflectance with angle of incidence is illustrated for eight metals in Fig. 5. These are first surface mirrors made by evaporating metal onto glass, and the glass here serves the sole purpose of being a backing for the metal. Silver, aluminum, nickel, chromium, and molybdenum have maximal regions near 30 degrees from the normal, while gold has practically constant reflectance up to 60 degrees. Copper and tungsten show a steady rise of reflectance from 0° to 90°. These and all other curves presented in this paper are extrapolated for a few degrees in the direction of unity reflectance at 90 degrees or grazing incidence.

A visual test was made to see if there was an actual approach to 100 percent reflectance at near grazing incidence. An observer faced a large white surface and held a mirror at arm's length in the direction of the surface. As the mirror was rotated toward grazing incidence, the dividing line between the surface and its image would vanish within about two degrees of grazing. The photometric sensitivity was probably about three percent, so that the indicated reflectance was 0.97, and every mirror so tested thus indicated perfect reflectance at 90-degrees incidence.

The silver and aluminum mirrors showed a minimum near 80 degrees and in the case of the latter metal, the reflectance near the tested point, at 82.5 degrees was about 7 percent lower than the useful maximum near 30 degrees.

In Figs. 5 and 6 a number in a circle near each curve tells how many mirrors were tested to get data for the curve. The mirrors of Fig. 6 are the same as in Fig. 5, but here the test was made on light that had passed through the glass to the metallic backing. The two groups of curves, therefore, show how the same metal film acts as a first and as a second surface mirror. In the latter case there is less tendency toward a maximum near 30 degrees, and there is also less tendency toward a minimum near 80 degrees. These changes could have been anticipated because at this angle the first surface of the glass plays an important part, and the glass reflectance is rising sharply at 80 degrees as was illustrated in Fig. 4.

A group of 14 kinds of polished metal mirrors (Fig. 7) that were either solid metal or plated by a chemical process were tested along with the evaporated mirrors. Silver in both the solid and evaporated form maintains an average of about 95 percent throughout the useful region, but the solid metal has less drop in the 80-degree zone. Cadmium has an unique characteristic in the pronounced peak at 40 degrees as compared with the low values at 0 degrees and 80 degrees. This

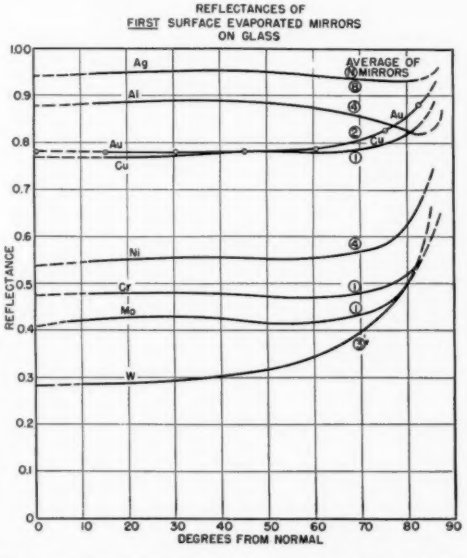

FIG. 5. Measurements on the metal or first surface of eight kinds of metals gave the above curves for the angle-reflectance characteristics. Silver and aluminum show minima near 80 deg. and all curves are extraplated toward perfect reflectance at 90° incidence. The numbers in the circles indicate the number of sample mirrors used to get an average value.

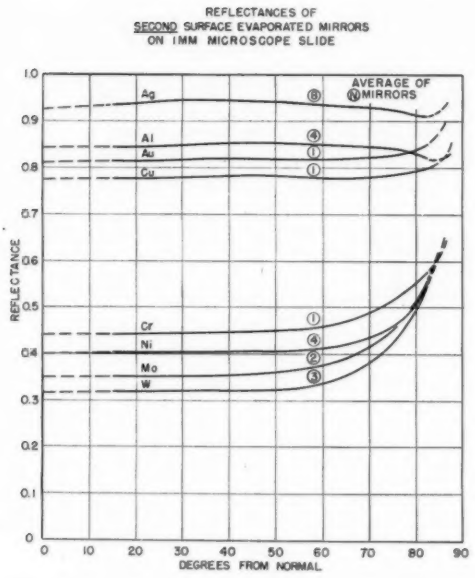

FIG. 6. These curves are for the mirrors of Fig. 5 tested as second surface mirrors. The characteristics are similar for the two sides, but there are several interchanges in relative positions, notably between nickel and chromium.

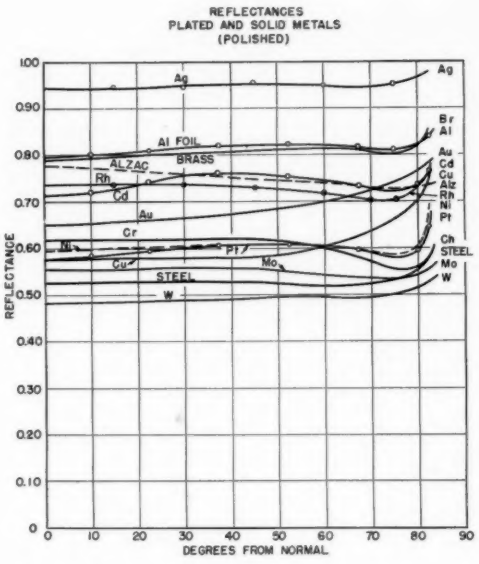

FIG. 7. These 14 reflectance curves are for a group of plated and solid mirrors (see Table I for details) that were polished to the best obtainable brightness without regard to optical flatness. Twelve metals showed at least traces of a minimum reflectance near 80 deg. and only two, copper and gold, were without this minimum.

may explain some of the discordant data on cadmium that have appeared in the literature.

A comparison of the data of these polished metals with evaporated metals shows the latter to be, in general, inferior. As a rule an evaporated film cannot be polished on account of its softness, and the observed differences are, therefore, permanent for the present at least.

METHODS OF RATING MIRRORS

A number of methods of arranging a test for reflectance have been suggested and used; the simplest of these is the measurement of light at 45-degree incidence and reflection. An ordinary direct vision photometer, a block of magnesium carbonate, and a steady source of light are all that is required for this type of test. The brightness of the carbonate is observed directly and then its image is observed in the mirror. The ratio of image brightness to direct brightness is the 45-degree reflectance. This method may yield results of high precision, but as noted in reviewing the work on the angular characteristics of reflectance, the 45-degree point possibly may not be typical for a surface that also receives light at other angles. This question will be given further attention.

In Table I, summary of reflectances, thirty-seven kinds of mirrors are ranked in their order of merit as judged by their 45-degree reflectance (R_{45}). The first column gives the metal or alloy, the second the type of mirror, whether first or second surface, solid or plated, and the third the number of samples included in the test figures. Under the heading "45" the first column gives the rank, and the second the 45-degree reflectance. The highest value is given by silver evaporated on the first surface of a microscope slide, and the lowest value, at the foot of the column, is for the two surfaces of a microscope slide without coating. The figures for the glass are included because the first surface reflectance and the absorption in the glass both have an influence on the performance of a second surface mirror. The amount of light reflected from the front surface of the glass is about half the given figure and the loss of light due to absorption in passing twice through the glass is over 3 percent for the glass

TABLE I. Summary of reflectances.

Metal	Surface or backing	Samples tested	R_G Rank	R_G R	S_{0-90} Rank	S_{0-90} R	$S_{0-\infty}$ Rank	$S_{0-\infty}$ R	$P_{0-\infty}$ Rank	$P_{0-\infty}$ R
Silver	First	8	1	0.952	2	0.944	2	0.946	1	0.948
Silver	Solid	1	2	0.950	1	0.948	1	0.948	2	0.946
Silver	Second	5	3	0.943	3	0.938	3	0.941	3	0.941
Al+2% Cu	First	2	4	0.903	4	0.892	4	0.900	4	0.899
Al+2% Mg	First	5	5	0.883	5	0.875	5	0.884	5	0.883
Al	First	8	6	0.878	7	0.868	7	0.877	7	0.872
Al+½% Sb	First	2	7	0.876	6	0.870	6	0.878	6	0.878
Al+½% Sb	Second	2	8	0.848	8	0.850	8	0.849	8	0.849
Al	Second	8	9	0.839	9	0.832	9	0.836	9	0.834
Gold	Second	1	10	0.822	10	0.820	10	0.819	10	0.820
Al Foil	Solid	1	11	0.820	11	0.812	11	0.813	11	0.813
Al+2% Cu	Second	2	12	0.809	12	0.811	12	0.809	12	0.809
Brass	Solid	1	13	0.806	13	0.806	13	0.804	13	0.804
Copper	First	1	14	0.783	14	0.783	14	0.780	14	0.780
Copper	Second	1	15	0.783	15	0.780	15	0.780	15	0.780
Gold	First	1	16	0.756	16	0.767	16	0.755	16	0.756
"Alzak"	Solid	1	17	0.744	17	0.748	17	0.753	17	0.751
Cadmium	Plated	1	18	0.744	18	0.741	18	0.746	18	0.745
Rhodium	Plated	6	19	0.730	19	0.726	19	0.728	19	0.729
Al+2% Mg	Second	5	20	0.706	20	0.707	20	0.705	20	0.706
Gold	Solid	1	21	0.673	21	0.684	21	0.669	21	0.670
Chromium	Plated	1	22	0.618	22	0.606	22	0.618	22	0.617
Nickel	Plated	1	23	0.608	23	0.600	23	0.602	23	0.601
Platinum	Solid	1	24	0.607	25	0.597	24	0.598	24	0.598
Stellite	Solid	1	25	0.594	26	0.594	25	0.591	25	0.590
Copper	Solid	1	26	0.581	24	0.600	26	0.583	26	0.585
Molybdenum	Plated	1	27	0.553	28	0.549	27	0.554	27	0.553
Nickel	First	1	28	0.551	27	0.559	28	0.550	28	0.551
Steel	Solid	1	29	0.523	29	0.527	29	0.526	29	0.526
Tungsten	Solid	1	30	0.491	30	0.492	30	0.490	30	0.492
Chromium	First	1	31	0.473	31	0.472	31	0.468	31	0.475
Chromium	Second	1	32	0.448	32	0.460	32	0.447	32	0.447
Molybdenum	First	2	33	0.418	33	0.429	33	0.422	33	0.421
Nickel	Second	1	34	0.406	34	0.416	34	0.404	34	0.406
Molybdenum	Second	2	35	0.360	35	0.376	35	0.357	35	0.357
Tungsten	Second	1	36	0.322	36	0.342	36	0.322	36	0.323
Tungsten	First	1	37	0.309	37	0.331	37	0.303	37	0.304
All Metals	—	81		0.679		0.680		0.677		0.677
Glass	Both	1		0.095		0.149		0.092		0.094

used in these tests. This loss, of course, influences the performance of a second surface mirror.

In this tabulation there are eleven metals and alloys that have been used to make both first and second surface evaporated mirrors. The average reflectance of the first surface mirrors is 0.707, while the average of the second surface is 0.662, a difference of 0.045. Since the loss by absorption in the glass is 0.030, the first surface mirrors would be about 0.020 better reflectors if the glass could be made so thin that the absorption would be negligible. Copper and the aluminum-copper alloy coatings gave almost identical figures for the two sides, while gold and tungsten gave better results as second surface reflectors. The seven other metals gave figures from one percent to seventeen percent higher as first surfaces.

A comparison between the same metal evaporated and in the solid or plated form shows silver to give identical results, gold to be much better in the first surface form and tungsten much better as a polished solid. The evaporated tungsten has a strong tendency to form a granular diffusing surface, or in shop parlance, "bloom."

A word of explanation should be given for the data on Stellite. The only available sample in usable form was about twenty-three years old, and it had not been repolished since first made. It was cleaned before testing, with the results given, and then repolished. The fresh surface gave practically identical results; therefore we may infer that the depreciation in twenty-three years was negligible. Stellite, being an alloy of variable composition, probably has been im-

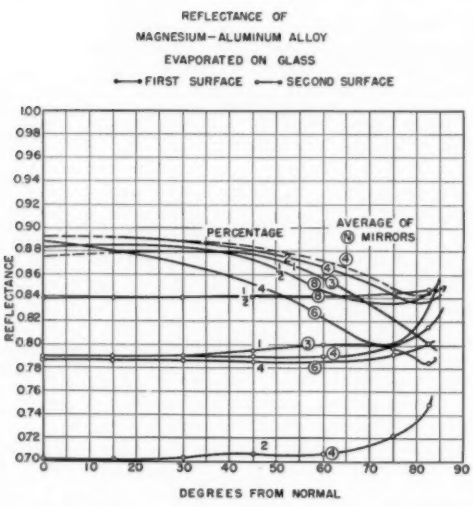

FIG. 8. A group of magnesium-aluminum alloy mirrors were tested on both surfaces with the results shown above. There is no obvious relationship between the two surfaces, and one group of 4 containing 2 percent magnesium was close to the best as a first surface mirror and decidedly the poorest as a second surface. See test for percentages in charge placed on the evaporating filament and percentages of magnesium found on the mirrors.

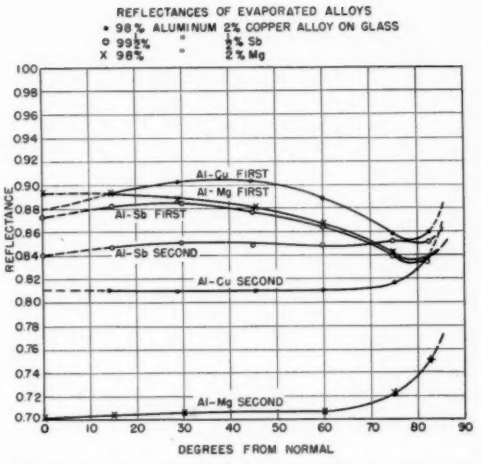

FIG. 9. This is a group of the best samples obtained with various alloys of copper, magnesium, and antimony with aluminum. As first surfaces they showed deep minima at 80 deg. and no minima as second surface mirrors.

proved since the mirror which was measured was made. A searchlight mirror was tested at 45 degrees and the reflectance was found to be 0.679. Data could not be obtained at the other angles, because the mirror was too large to be placed in the gonioreflectometer.

A number of reflectometers that have been used successfully are based on the principle of illuminating the test surface at all angles and observing the fraction of the light reflected. This might be called spherical reflectance as it is the same as would be obtained by making the test mirror part of the surface of a relatively large integrating sphere and observing what effect the mirror has on the brightness of the sphere. Here the fraction of light incident on the mirror between angles a and b is

$$F_{a-b}=\cos a-\cos b$$

and the spherical reflectance S_{0-90} is

$$S_{0-90}=\sum_{0}^{90} R_{(a+b)/2}\,(\cos a-\cos b),$$

where $R_{(a+b)/2}$ is the reflectance in the middle of the zone from a to b.

The data under the heading S_{0-90} in the tabulation are computed from the data of the curves previously given, using this summation formula. The rank on this basis is also given and it will be noted that in a number of cases the tabulation of rank numbers does not follow the order of the natural numbers. In some cases the difference in rank is caused by a difference of only a fraction of one percent, and hence is hardly significant. But there are fourteen cases where there is a difference of 0.010 to 0.022 between the two ways of testing and rating. These differences may be considered significant. In the case of interlaboratory comparisons they might call for rechecking.

By reference to the curves showing the variation of reflectance with angle of incidence it will be seen that the region for 70 degrees up to grazing incidence gives rather unpredictable values. The inclusion of this region in photometry may either raise the general average or lower it, depending upon the absence or presence of a dip in the curve near 70 degrees. Since mirrors are seldom used to reflect light at more than 60 degrees from the normal, these changes in the S_{0-90} average are rather fictitious from a practical point of view. In the following paragraphs two other methods of weighting reflectances are given, and finally a comparison between four methods is made to see if any of them have outstanding merits or demerits.

In the column headed S_{0-60} the summations are carried only to 60 degrees, which is an assumed limit of practical use and the average is expressed by the formulae

$$S_{0-60}=\frac{1}{0.75}\sum_{0}^{60} R_{(a+b)/2}\,(\cos a-\cos b),$$

where the factor 0.75 is derived from the fact that the sum of the spherical zones up to 60 degrees amounts to three quarters of a complete sphere. An examination of the data of this column will show not a single case where the reflectance varies by 0.010 from the 45-degree column. It is thus seen that an average extending over the useful angles of incidence is in better agreement with the 45-degree reading than with the average including all angles up to grazing.

There is a fourth way in which mirrors might be evaluated. The paraboloid used in the automobile headlight is of such importance and exists in such vast numbers that it should be given special consideration. The form of the paraboloid is such that a ray leaving the filament at an angle of c degree from the axis strikes the reflector at an angle of incidence of $c/2$ degrees, and the last useful ray at 120 degrees from the axis has an angle of incidence of 60 degrees. From this relationship of zone to angle of incidence we derive

$$P_{0-60}=\frac{1}{0.75}\sum_{0}^{60} R_{(a+b)/4}\,(\cos a-\cos b)$$

for the weighted average reflectance of a paraboloid having a lamp that gives a uniform distribution of light.

The agreement of averages found on the basis of this very practical viewpoint with the averages found for 45 degrees is excellent, and again not a single disagreement as large as 0.010 will be found in the tabulation. On the basis of this and the previous comparisons, it seems that three out of the four methods will yield concordant data and only the case where all angles are included in the computation is there frequent disagreement with the others.

In considering the relative merits of two metals, the matter may be decided by noting which is the better reflector without paying particular attention to the actual reflectances. In the first data column of the tabulation the mirrors are arranged and numbered according to their reflectance at 45 degrees' incidence. In the second data column where the figures are for the average reflectances from 0 to 90 degrees with completely diffused illumination, the order of rank varies in nine instances and taking differences between rank numbers on the same line, the sum of such differences is found to be ten. When a similar comparison is made between the 45-degree measurement and the summation up to 60 degrees, the sum of the differences amounts to four, while 45 degrees compared with the paraboloid gives a sum of only two. Again it is found that three methods are in agreement and the fourth, the summation from 0 to 90 degrees, is somewhat isolated.

No great accuracy can be claimed for this ranking method because in a number of cases the order depends upon only a few tenths of one percent in reflectance.

One fact this calculation brings out strongly is the failure of the averages for the four columns to yield critical data. The averages are, in order, 0.679, 0.680, 0.677, and 0.677. The differences here are without significance, and the conclusion might be drawn that the four methods yield

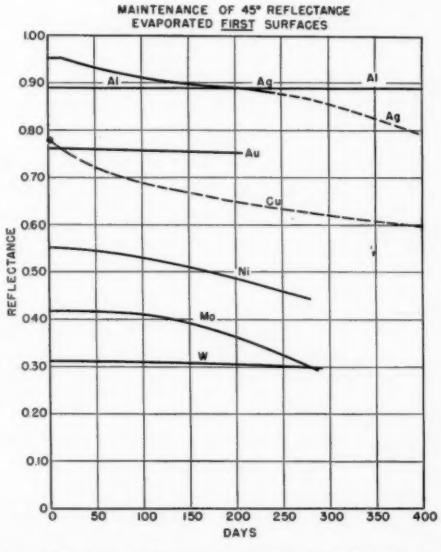

FIG. 10. These maintenance curves show how seven first surface metals maintain their 45-deg. reflectance with age when standing exposed in a laboratory room.

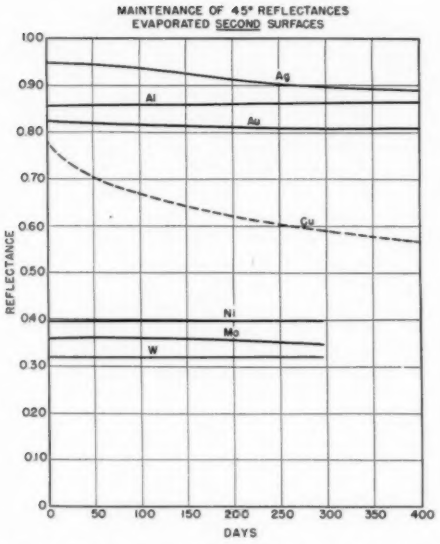

FIG. 11. The same metals as in Fig. 10 are here tested as second surfaces. The protection afforded by the glass helps the maintenance of silver, nickel, and molybdenum but has slight value in preventing copper from depreciating.

practically identical results. An inspection of the data, particularly between the first two data columns will show the first six mirrors in the 0–90-degree column to give lower figures than in the 45-degree column. On the other hand, the last six mirrors give higher figures when the same comparison is made; this reversal is connected with the presence or absence of a dip in the reflectance curves at near 70 degrees. The differences are about equally distributed between positive and negative values, and it is only when individual mirrors are considered that the real disagreements of the four methods become apparent.

The total summation method, S_{0-90} is at a distinct disadvantage as a method for deriving useful data, and it seems that from the standpoints of definiteness, simplicity and the yielding of a practical figure, the 45-degree method has rather distinct advantages.

ALUMINUM ALLOYS

Since pure aluminum shows a high degree of stability and is, next to silver, the best metal tested, it was thought worth while to make different alloys to see if any combination better than the pure metal could be found. Magnesium, antimony and copper mirrors were made and tested over a period of a half year or more.

Mixtures containing ½, 1, 2, 4, and 8 percent magnesium were evaporated onto glass and tested as both first and second surface mirrors. The pure aluminum mirrors that were made as a blank or control gave a reflectance of 0.87 as first surface mirrors and all the mixtures gave reflectances close to 0.90, indicating an improvement of 3 percent. They were so consistent that it seemed advisable to check on the percentages of magnesium in the mirror coating. Spark spectrograms showed that ½ and 1 percent mixtures gave coatings of ½ and 1 percent, respectively, but that 2, 4, and 8 percent mixtures all gave approximately 2 percent magnesium on the glass. From this observation it is evident that the magnesium vaporizes at a higher rate than the aluminum, and the deposit is first rich in magnesium and then poor as the evaporation proceeds. The first alloy evaporated is caught on the shield used while the surface of the alloy drop is being cleaned by evaporation, and the final result is a two percent aluminum-magnesium alloy on the glass.

The angular reflectance characteristics of the

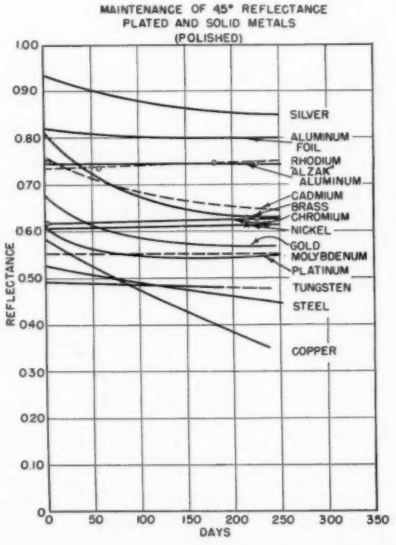

FIG. 12. These 14 metals show all degrees of stability with age, and in several cases a small appreciation in 250 days is probably due solely to photometric errors.

alloys are given in Fig. 8 for both the first and second surfaces. The numbers in rings attached to each curve tell the number of mirrors included in the average. There is seen to be but little consistency in the relation between original alloy and first surface reflectance. The nearest approach to consistency is an observed relation between first and second surfaces. The better the first surface, the poorer the second surface, seems to be the rule, and this alloy, while good as a first surface, does not appear suitable for second surfaces. The 4-percent mixture has an extreme drop at 75 degrees on the first surface and an almost constant reflectance at all test points on the second surface. In general, the characteristics of the two surfaces are markedly different, and the inevitable contrast with silver or with pure aluminum does not present the alloys in as favorable a light as was at first hoped for.

The curves of Fig. 9 for aluminum-copper and aluminum-antimony indicate that the copper alloy in particular has possibilities which have not been explored. The 2 percent aluminum-magnesium alloy is included in Fig. 9 so that the three alloys can be compared.

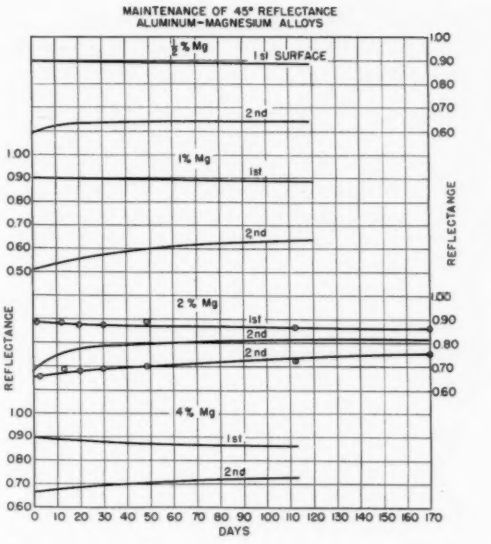

FIG. 14. These aluminum magnesium alloys show good reflectance and good maintenance as first surface mirrors, but the second surface has low reflectance combined with a definite appreciation. This increase is presumably due to an initial excess of magnesium next to the glass and as this layer migrates into the aluminum the composition approaches that of the first surface.

VARIATION OF REFLECTANCE WITH TIME

A number of things may, and do, happen to a newly made mirror. The evaporation process seems to lay down the metal in a soft layer that has low cohesion and either a fine or no crystalline structure. Aluminum deposits as a film that changes rapidly with time so that at the end of a few days a noticeable increase of mechanical strength occurs, and it has then reached a relatively stable form. Upon removing from the evaporating bell and exposing to the atmosphere, the surface of the aluminum promptly oxidizes, and the hardening process which comes later seems to be due to the formation of crystals rather than to oxidation. If the film is too thick, there is a tendency for pinholes to form immediately and these, when examined under the microscope, are found to be radial cracks that may be separation lines between adjacent crystals.

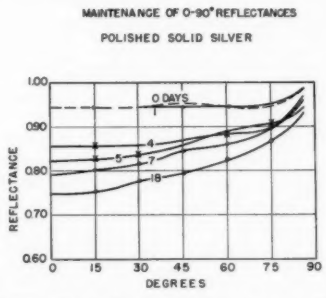

FIG. 13. The $R-\theta$ characteristics of a repolished silver mirror show that the reflectance at angles near the normal depreciates faster with age than the reflectance near grazing. As a result the characteristic curves change shape and they illustrate the danger of making assumptions as to shape of the $R-\theta$ curve in any particular case.

An x-ray examination shows the aluminum of an old mirror to be definitely crystallized, and this demonstrates the change with age that takes place in the metal.

The hardening of the metal may be accelerated by heating the mirror to about 180°C. Tests on a few mirrors indicate that there is no increase of reflectance in a new mirror, but when an old mirror is heat treated, there is an improvement, and the resultant surface has better permanence. Four mirrors at age 70 days were tested and then heat treated. The retest gave:

Pure aluminum. Reflectance at 45 degrees.

Untreated	First Surface	0.884	Second Surface	0.856
Treated	First Surface	0.897	Second Surface	0.867.

A test at 571 days gave substantially the same reflection as those on the second line, so the heat treatment may give not only a better mirror, but also a more permanent one.

In Fig. 10 the depreciation curves are given for seven pure metals as first surfaces. Aluminum, gold, and tungsten are highly stable, while silver, copper, nickel, and molybdenum depreciate to an important degree in from 200 to 400 days. Portions of the silver and copper curve are dotted because the test points were not close enough in time to determine accurately the curvature. The depreciation curve for the same metals as second surfaces are shown in Fig. 11. The protection given by the glass evidently greatly decreases the depreciation of silver, nickel, and molybdenum, while copper depreciates at about the same rate on both the protected and exposed surfaces.

The depreciation characteristics of fourteen polished metals, either solid or plated, are given in Fig. 12. The most stable metals are aluminum, rhodium, chromium, nickel, and platinum, while the most unstable are copper, steel, cadmium, brass, and silver. The mirrors were dusted and wiped lightly with "kitten's ear" cloth at each photometric test, but care was taken to stop short of repolishing.

The solid silver mirror was tested after 230 days and found to reflect 84.7 percent in place of the original 95.0 percent. After this test, the mirror was repolished and tested on the same and the succeeding day. The 45-degree reading was 0.950, the original value. After four days the surface had visibly dulled and four more angular analyses were made up to the eighteenth day. In this period the silver depreciated almost as much as it did in 382 days after the original polishing. The rapid depreciation was evidently due to the polishing material, which was a metallographic polishing preparation of magnesium oxide and not the chemically pure magnesium oxide that was used originally.

The depreciation was not the same at all angles, and in Fig. 13 the angles near the normal are seen to vary more than those near grazing. This gave rise to a progressive change of color with time that also involved the angle of observation.

The depreciation test on the aluminum-magnesium alloys (Fig. 14) brought out an unexpected phenomenon. The first surfaces of these alloys showed a slow depreciation, but the second surfaces appreciated as much as 13 percent in one hundred and ten days.

Since the aluminum and magnesium are evaporated at different rates, the alloy on the mirror may be stratified, with a higher magnesium content next to the glass. This layer would diffuse through the aluminum and bring the second surface nearer to the pure aluminum state during the period of these tests. The original reflectances were so low, however, that even if the appreciation continues for a long period the second surface alloy would hardly become a serious competitor of the pure metal. It was also found that the 2-percent aluminum-copper alloy was less stable than the pure metal, and, therefore, the heat treated aluminum remains the most stable of the metals that have high reflectances.